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PHYSICAL HYDRAULIC MODELS ASSESSMENT OF PREDICTIVE CAPABILITIES

Report 2

MOVABLE-BED MODEL OF GALVESTON HARBOR ENTRANCE

by

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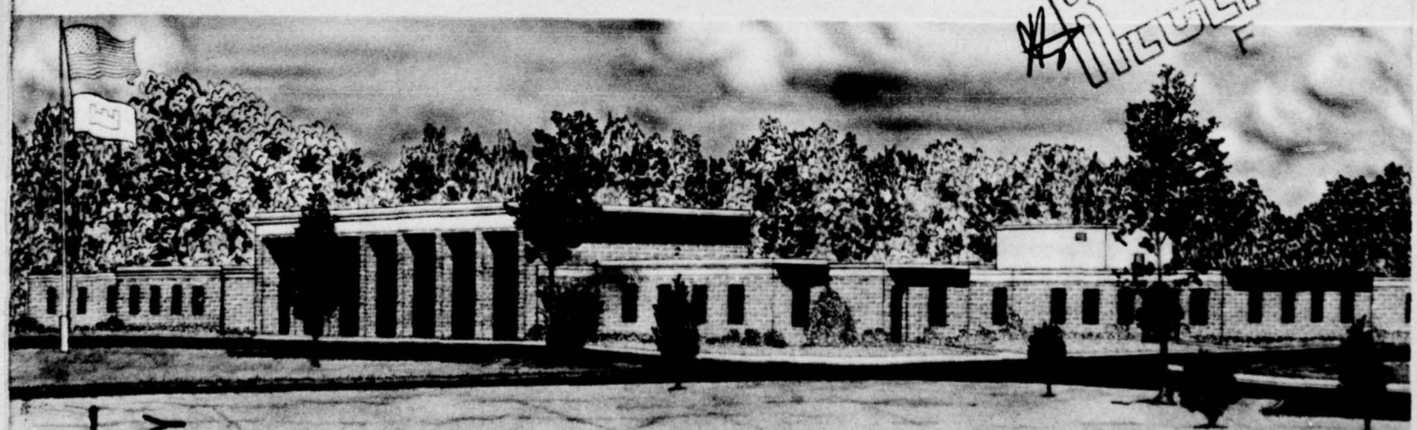

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This study evaluates movable-bed physical hydraulic model predictions of sedimentation effects arising from channel realignment and deepening in Galveston Harbor entrance, Texas. Comparisons of model predictions and observed behavior for 6 years following completion of channel realignment showed that qualitative predictions of an arrest of undermining of the north jetty were correct and that the predicted relative increase in total

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maintenance dredging was reasonably close. The primary objective of the original study--to improve channel alignment for navigation safety--was achieved but is not addressed in this report. Detailed analysis showed that absolute model predictions of dredging volumes were somewhat low in the approach channel, essentially correct in the outer bar channel, and considerably low in the inner bar channel. Locations of scour and fill were accurately predicted for the navigation channel but volumes of the changes were underestimated by the model. Large zones of scour and fill in the entrance were approximately similar in model and prototype.

Differences in model and prototype results are believed to be due to scale effects and insufficient prototype data. It is concluded that movable-bed modeling is a feasible, though difficult, technique and that steps to improve model similitude will improve similar future movable-bed model studies.

SUMMARY

The primary objective of this study is to define the accuracy of movable-bed model predictions of shoaling in Galveston Harbor entrance after navigation channel realignment; a secondary objective is to gain an improved understanding of movable-bed modeling techniques so that the value of such models can be increased.

Galveston Harbor entrance is a jettied tidal inlet on the Texas coast with a federally maintained navigation channel. The entrance channel is composed of three sections--the approach channel in the Gulf of Mexico, the outer bar channel just inside the jetties, and the inner bar channel passing through the inlet throat. Maintenance dredging volumes for the entrance channel have averaged more than 1,000,000 cu yd per year for more than 25 years. Shoaling in the inlet and navigation channel is affected by tidal currents, short-period waves and their resulting currents, and local and tropical storms. Inlet sediments are predominantly fine sands characteristic of the littoral zone.

The Galveston Harbor entrance model study was conducted at the U. S. Army Engineer Waterways Experiment Station to determine a channel alignment that would result in safe navigation conditions and halt the undermining of the north jetty, and to predict shoaling characteristics of the realigned channel. The study was conducted with a combination fixed-bed and crushed coal movable-bed model with length scales of 1:100 vertically and 1:500 horizontally. Subsequent to the model study a realignment plan that resulted in the safest and shortest navigation channel, provided protection from undermining of the north jetty, and indicated a modest overall shoaling increase was constructed at Galveston.

Comparisons are made of model predictions and observed prototype behavior for 6 years following completion of channel realignment. Analysis showed that the qualitative prediction that undermining of the north jetty would be halted was correct and that the predicted relative increase in total maintenance dredging was reasonably close to that experienced in the prototype. One of the primary objectives

of the original study--to improve the channel alignment for navigation safety--was achieved, but is not addressed in this report.

Detailed comparisons of quantitative model predictions with prototype experience after construction are made for dredging volumes and for bed changes. Predictions of relative increases in reported dredged volumes were quite accurate for the combined approach and outer bar channels and low for the inner bar channel. Absolute dredging volumes and absolute volumes adjusted for dissimilar dredging practices in model and prototype show that the model dredged volumes were somewhat low in the approach channel, essentially the same as the prototype outer bar channel, and substantially low in the inner bar channel. Large zones of scour and fill were in approximately similar locations in model and prototype but the location of some smaller zones were not the same. Scour and fill in the navigation channel were similar in location but on a much smaller volume scale in the model.

Similitude requirements for movable-bed modeling are not well developed, and the complexity of the factors controlling coastal sediment transport creates conflicts between desired scaling criteria and practical limitations on model size and operating procedures. As a result, the modeler's skill and interpretation of results are of supreme importance in movable-bed modeling.

Based on the model-to-prototype ratio of the particle densimetric Froude number, F_* , examination of potential scale effects in model sediment transport reveals that sediment transport rates in the model may have been too low. For tidal currents, the average ratio was about 0.01 to 0.04 instead of the ideal value of 1 and for waves the ratio is estimated to have been about 0.4. Another potential scale effect was the relatively low number of flow reversals during a simulated year in the model. This, coupled with prolonged maximum ebb and flood flows, may have reduced the tidal rearrangement of sediments in the inlet by repeated changes in direction of transport.

It is concluded that most of the model's qualitative predictions and overall quantitative predictions were reasonably close to prototype behavior for the 6-year period studied, but that most of the detailed

quantitative predictions were not. Discrepancies are believed to be primarily due to a low rate of sediment supply to the model inlet, a low tidal current transport capacity, and inexact location of some scour and fill areas due to a lack of definitive prototype data. Movable-bed modeling is concluded to be a feasible, though difficult, technique for the solution of similar problems in similar inlets.

Recommendations for successful movable-bed modeling of similar inlets include obtaining detailed and comprehensive prototype data whenever possible; choosing scales and model sediments that approach a densimetric particle Froude number ratio of 1; minimizing distortion of hydrodynamic similitude; designing model operation to properly account for sediment sources and storm effects found to be important at the site; and interpreting model results in terms of relative changes.

PREFACE

The research described in this report was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) under the Coastal Engineering Research Area of the Corps of Engineers Civil Works Research and Development Program sponsored by the Office, Chief of Engineers, U. S. Army.

Personnel of the Hydraulics Laboratory of WES performed this study during the period 1974 through October 1975 under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory; F. A. Herrmann, Jr., Assistant Chief of the Hydraulics Laboratory; R. A. Sager, Chief of the Estuaries Division; G. M. Fisackerly, Chief of the Harbor Entrance Branch; and W. H. McAnally, Jr., Estuarine Research Projects Manager. Mr. J. V. Letter, Jr., was Project Engineer. Messrs. Letter and McAnally prepared this report.

Directors of WES during the course of this study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
acre-feet	1233.482	cubic metres
square feet	0.09290304	square metres
square miles (U. S. statute)	2.589988	square kilometres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet per second	0.3048	metres per second
cubic feet per second	0.02831685	cubic metres per second
feet per second per second	0.3048	metres per second per second
degrees (angle)	0.01745329	radians

PHYSICAL HYDRAULIC MODELS: ASSESSMENT OF PREDICTIVE CAPABILITIES

MOVABLE-BED MODEL OF GALVESTON HARBOR ENTRANCE

PART I: INTRODUCTION

Objectives

1. The primary objective of this research study is to define the accuracy of the movable-bed physical hydraulic model predictions for Galveston Harbor entrance. The model study predicted the optimum channel alignment, in conjunction with deepening, for minimum shoaling and maintenance dredging in the entrance channel. By evaluating these model predictions, greater understanding of the capabilities and limitations of movable-bed physical modeling will be developed.

2. A secondary objective of this study is to gain an improved understanding of modeling techniques so that the value of movable-bed models can be increased.

Background

3. Physical hydraulic models have been successfully used for many years to predict the response of estuaries and harbors to alterations such as dredging, landfills, structures, and flow regulation. Unfortunately, little attention has been given to careful comparisons of model predictions with prototype behavior after the proposed modifications to the system have been made. Model predictions of tidal elevations and phases, current velocities, circulation patterns, and salinity intrusion are considered highly reliable. Other phenomena such as pollutant and sediment transport are considered to be less reliably reproduced in physical models. With a lack of evaluation of model predictions, the degree of confidence that may be placed in predictions of these various phenomena has not been defined. Particularly, the reproduction and

prediction of pollutant and sediment transport have suffered in the absence of model evaluations. Detailed studies of transport phenomena could develop guidelines for improved modeling techniques.

4. There are several reasons for this lack of comparison between model prediction and prototype behavior, which is termed postconstruction verification or model confirmation. First, resources are seldom available to follow up a model study and prototype project with a costly postconstruction study if the project appears to be functioning satisfactorily. Other prototype problems usually demand attention and money that might have been applied to follow-up studies. Secondly, many projects are changed before construction due to considerations that are not relevant to the model study; therefore, detailed comparisons between model tests and prototype results are not possible unless costly additional model tests are run with the appropriate boundary conditions. Finally, some model studies show a project to be unfeasible and the project is not constructed. Consequently, there is no basis for comparison to evaluate the model's prediction.

5. Postconstruction verification of a physical model can be attempted under two conditions. First, the project constructed in the prototype system may match one of the project plans tested in the model. In this case, the postconstruction prototype data are directly comparable with the model data if sufficient care is taken to match the prototype data boundary conditions with those of the model plan test.

6. The second condition occurs when the project constructed in the prototype is altered from the plan tested in the model, but the physical model is still in existence. If the cost is not prohibitive, necessary changes may be made in the model to duplicate the actual prototype construction and additional model tests may be conducted. Postconstruction prototype data collection and changes in the model can proceed simultaneously, and then additional model tests can be performed under the same boundary conditions as during the prototype data collection. The model and prototype data can then be compared and analyzed.

7. The increasing environmental awareness of recent years has resulted in a demand for more detailed evaluations of the effects a

particular project will have on the sometimes delicately balanced ecosystem of the estuary or harbor. Of special interest are the effects on salinity intrusion, pollutant transport, and sedimentation. These effects must be determined in order for an Environmental Impact Statement (E.I.S.) to be compiled. It is not uncommon for large sums of money invested in project design or allocated for project construction to remain idle while awaiting the E.I.S. For many projects, the fastest and most accurate means available to evaluate the physical effects of the project which might influence the ecosystem is through a physical model study.

8. This requirement for detailed model predictions challenges the modeler to develop a better understanding of the physical phenomena being modeled, to define the accuracy to which the model reproduces the phenomena, and to develop better modeling techniques to increase the accuracy of the model. In response to this challenge, in 1971 the Office, Chief of Engineers (OCE) authorized the U. S. Army Engineer Waterways Experiment Station (WES) to begin a series of confirmation studies. This report is the second study of the series; the first study was of the Delaware River model.[1]

9. The Galveston Harbor entrance channel model study was conducted at WES during the period May 1960 through February 1966. The objectives of the original model study[2] included determination of a means for protecting the north jetty from undermining by tidal currents and determination of the shoaling characteristics of the inner and outer sections of a deepened entrance channel. Other objectives of the original study that are not addressed in this report were to develop a channel realignment for safer navigation and to determine the best locations for additional anchorage areas. One of the deepening and realignment plans tested in the model was constructed in the prototype. The feasibility of the plan was judged in part on model results which indicated that while a deepened channel along the proposed alignment would require increased maintenance dredging, the additional cost would be partially offset by a seaward shift in the shoaling distribution. The purpose of this report is to evaluate the accuracy of the model predictions of

maintenance dredging requirements and changes in the inlet bed as a result of this channel realignment and deepening.

Approach

10. Postconstruction verification of a physical model can be accomplished by two methods of data comparison and analysis. The more direct method is to compare postconstruction prototype data with model test predictive data. This is most useful for a direct indication of the quantitative accuracy of the model predictions.

11. The other method is a comparison of prototype data prior to construction with prototype data after construction of the project is completed. This defines the relative effects of the project construction, usually expressed as a percentage increase or decrease. This relative prototype change can then be compared with the relative change predicted by the model. This method is useful when it is difficult to obtain postconstruction prototype data to match the boundary conditions of the model test, and additional model tests are not possible. It is also the most appropriate technique, since some model scale and boundary effects are removed from the results by comparison of model data with other model data.

12. For either method of model confirmation, care must be taken to match the postconstruction prototype boundary conditions (tide, freshwater flows, waves, etc.) during data collection with the conditions for the comparative test. This is true whether the comparative data are preconstruction prototype or postconstruction model data.

13. For the present study dealing with relatively long-term sedimentation, it is necessary to assume that the climatic conditions that prevailed prior to the prototype construction were essentially the same as those encountered after the channel realignment was completed. This is a reasonable assumption provided the periods used for data averaging are of sufficient length. This report discusses the record length and its effect on the results.

Movable-Bed Modeling

14. Successful modeling requires the development of realistic similitude requirements for the phenomena to be studied and then making satisfactory compromises between similitude requirements and practical limitations on scales, materials, and methods. A prominent example is the use of distorted-scale hydraulic models as a compromise between the requirements of Reynolds and Froudian similitude on one hand and practical limitations on model size on the other. Compromising similitude requirements may result in scale effects, errors in reproduction of some phenomena due to the choice of scales. However, this compromise is an essential element of modeling practice.

15. The purpose of this section is to describe some commonly accepted similitude requirements for modeling of tides, waves, currents, and sediment transport, and the compromises that are necessary in a model combining these phenomena. Possible scale effects are then discussed.

Hydraulic similitude

16. Modeling of tides and currents is usually based on Froudian dynamic similarity and distorted geometric similarity. For a given horizontal length scale, distortion of length scales (larger vertical scale than horizontal scale) increases model velocities and depths, minimizes viscous scale effects and permits economical model size. Scale relations for tides and currents are derived in References 3, 4, and others and those derivations are not repeated here; instead, Table 1 summarizes scale relations for tides and currents according to Froudian similarity.

17. Also shown in Table 1 are scale relations for modeling of wind waves in distorted-scale physical models. Short-period wave models are often undistorted since distortion prevents simultaneous accurate modeling of diffraction and refraction. In a distorted-scale model, either diffraction or refraction must be chosen to be modeled correctly and the wave period ratio then chosen accordingly. The error in wave heights due to the effect not modeled may not be great, but it

will occur. Refraction due to wave-current interaction is poorly understood, but it seems to be dependent[6] upon the wave steepness (H/λ),* relative water depth (h/λ) and a current parameter (uT/λ). If the wave period scale for refraction (Table 1) is used, these parameters will be scaled correctly.

Sediment transport similitude

18. Sediment transport processes are complex and poorly understood, which makes quantitative descriptions and thus similitude requirements difficult to develop. This report deals only with noncohesive sediments, for which some similitude requirements may be deduced.

19. In movable-bed modeling, the problems involved in combining similitude requirements for hydraulic behavior with those of sediment characteristics and sediment-water interaction at first seem to be insurmountable; and compromises beyond those used to generate Table 1 are necessary. Hydraulic similitude often must be sacrificed in order to obtain sediment transport similarity; however, loss of hydraulic similarity must be approached with caution to avoid forcing the model to reproduce observed prototype behavior (verification) without retaining the model's ability to faithfully reproduce the prototype's response to changed conditions. Hydraulic similitude should at least be a starting point in the verification process.

20. The most common approach to developing scaling criteria for noncohesive sediment transport is to use forms of the dimensionless Shields parameters. The first of these parameters can be expressed as a particle densimetric Froude number given by

$$F_* = \frac{u_*^2}{\frac{\gamma' g d}{\gamma}} \qquad (1)$$

where

u_* = shear velocity $= \sqrt{\frac{\tau_o}{\rho}}$

τ_o = average bottom shear stress

ρ = density of water

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

γ = unit weight of water

γ' = submerged unit weight of sediment particles = $\gamma_s - \gamma$

γ_s = unit weight of sediment particles

d = representative sediment grain size

g = acceleration due to gravity

The parameter F_* corresponds to Einstein's[7] shear intensity function.

21. The other parameter used by Shields is a particle or shear Reynolds number given by

$$R_* = \frac{u_* d}{\nu} \tag{2}$$

where ν = kinematic viscosity of water.

22. A number of other parameters for defining similitude conditions are potentially important to the coastal movable-bed model. Similarity of grain-size distributions is usually ignored; but in situations where grain sorting plays a significant role, it should be considered. The ratio of grain density to water density affects sediment particle trajectories. Wave characteristics such as orbital velocity, orbit size near the bottom, and wave period can be combined to form several dimensionless groups including wave versions of R_* and F_*. Wave period compared with particle fall velocity can be an important consideration when waves contribute significantly to the transport process. These and other parameters are of potential importance, and various authors advocate different combinations to define similitude conditions. The choice of which parameters to use is dependent upon what the modeler perceives as the dominant transport mechanism and practical constraints upon model design.

23. Choice of a parameter involving the sediment transport rate is largely dictated by the location and mode of transport. Einstein's[7] transport function given by the following equation is often used.

$$\Phi = \frac{g_s}{\gamma_s}\sqrt{\frac{\rho}{\gamma_s' d^3}} \tag{3}$$

where

g_s = sediment transport rate in weight per time per unit width

ρ = water density

Such parameters are used to define a sedimentation time scale and any sediment transport formula found to be applicable can be used; however, in practice, time scales are usually determined empirically.

24. Equations 1 and 2 can be used as similitude conditions by replacing each variable with the model-to-prototype ratio of the variable. The conditions of similitude then become

$$F_{*r} = \Delta_{F_*} = \frac{u_{*r}^2}{\gamma_r' d_r} \tag{4a}$$

$$R_{*r} = \Delta_{R_*} = u_{*r} d_r \tag{4b}$$

where the subscript r indicates a model-to-prototype ratio of the subscripted variable and the Δ's are scale factors. Complete similarity of a parameter is said to occur when $\Delta = 1$, and deviation from $\Delta = 1$ results in scale effects. Deviation is permissible if the resulting scale effects are acceptable.

25. If the Δ's of Equations 4a and 4b are taken to be equal to 1, the following scale ratios result:

$$\gamma_r' = \frac{u_{*r}^2}{d_r} \tag{5a}$$

$$d_r = \frac{1}{u_{*r}} \tag{5b}$$

26. Equations 5a and 5b are useful as guides to model design, but it is generally conceded that strict adherence to these results (i.e., $\Delta = 1$) is not always necessary for satisfactory modeling results. In some cases, it may not be possible to satisfy Equations 5a and 5b and maintain a practical model sediment. For example, model geometric scales dictated by cost and characteristics of the site to be modeled

may cause Equations 5a and 5b to yield a sediment that is too fine or light for practical use. Small grain sizes and low specific gravities make model sediments tend to float and can prevent filling of the model with water and sounding of the bed by ordinary techniques. From the standpoint of their use by Shields, there would be little need to satisfy both F_* and R_* scaling unless incipient motion were an important aspect of the sediment transport to be modeled. For relatively rapid transport, an argument can be made for proper scaling only of F_* since it is the shear intensity relation used in Einstein's development. A discussion of some of the effects of deviation from Equations 5a and 5b is given in the section on scale effects (see paragraphs 36 and 37).

27. If Equations 5a and 5b are to be used for model design, the scale ratio for the shear velocity must be determined. Using the relation

$$u_* = \sqrt{ghS_e} \tag{6}$$

where

h = water depth

S_e = energy grade-line slope

then from the scale relations for depth and energy slope shown in Table 1,

$$u_{*r} = u_r\left(\frac{Y_r}{X_r}\right)^{1/2} = \left(\frac{Y_r}{X_r^{1/2}}\right) \tag{7}$$

where

u_r = current speed ratio

X_r = horizontal length scale ratio

Y_r = vertical length scale ratio

28. Kamphuis[5] uses experimental results on bed shear stresses due to waves to develop a different expression for u_*, resulting in the scale ratio

$$u_{*r} = u_r\left(\frac{k_{sr}}{Y_r}\right)^{3/8} \tag{8}$$

where k_s = equivalent bed roughness size.

29. For plane beds, k_s can be assumed approximately equa to a representative grain size, but when bed forms are present, k_s will be greater than a typical bed grain size. Although virtually all prototype sand beds and some models have undulating bed forms, it is commonly assumed that $k_{sr} = d_r$; actually, most model beds will result in k_{sr} less than d_r .

30. Another approach to development of similitude criteria is to nondimensionalize a sediment transport formula, forming dimensionless parameters such as those of Equations 1, 2, and 3. An advantage to this technique is that scale effects can be more readily determined than by the method shown above. Unfortunately, available sediment transport formulae are not sufficiently general to adequately describe the transport under a variety of flow conditions. In particular, there are no formulae known to be capable of adequately describing sediment transport by combined effects of waves and nonsteady currents. Thus, the equational approach, as this method is called, is not necessarily superior unless a formula is known to accurately describe the transport to be modeled.

31. An example of the equational approach is given by Christensen and Snyder[8] in which du Boys' bed-load formula is used to develop a scale relation for the grain-size ratio which the reference recommends for use when transport rates are high. The resulting equation can be expressed as

$$d_r = \frac{u_{*r}^{16/3}}{\gamma_r'^{8/3} \gamma_r^{4/3} u_r^{4/3}} \tag{9}$$

32. Most investigators use a representative grain size such as the mean grain diameter for d . Yalin[4] recommends that model sediments have the same grain-size distribution as the prototype. This is a difficult condition to satisfy and is probably unnecessary in most coastal models since a relatively narrow grain-size band often dominates local sediment deposition.

33. An additional requirement for accurate reproduction of shoaling is that the sediment supply to the area of interest be similar in model and prototype. If the effects of wave climate and tidal currents on transport are correctly reproduced, then sediment supply is sufficient if it is in adequate supply at the model boundaries. Maintaining a supply may require artificially feeding sediment at the model boundaries.

Scale effects

34. Evaluation of scale effects is an essential element in model design, test design, and interpretation of results. In cases where phenomena are well understood or where reliable descriptive equations are available, scale effects may be defined quantitatively. Unfortunately, many coastal phenomena are not well enough understood for quantitative definition of scale effects and evaluation of them must be qualitative.

35. Hydraulic scale effects due to viscosity are reduced by geometric scale distortion, but for reversing tidal flows there will often be short periods when the model flow will not be fully turbulent and scale effects due to unequal model and prototype Reynolds number will occur. As long as these periods are short with respect to the total time of bed-load transport, the effect on sedimentation will be minor.

36. If Equation 4a for Δ_{F_*} does not have a value of 1, the rate of sediment transport may be scaled incorrectly. For the most common case of Δ_{F_*} less than 1, the transport rate will be low since the intensity of shear is low. Adjustment of the time scale can compensate for an incorrect rate of transport, but a difficulty arises in that different time scales may be required for longshore transport, onshore-offshore movement, and transport by tidal currents.

37. Equation 4b can be viewed in somewhat the same manner as ordinary Reynolds similiarity in hydraulic similitude--if both model and prototype values of R_* are sufficiently large (greater than about 2), inexact similitude has minor effects. As with Equation 4a, approaching $\Delta_{R_*} = 1$ is most important when initiation of sediment motion is an important part of the transport. At high transport rates, the loss of similarity will have less effect. Thus a lack of similitude of R_* will be most troublesome during flow reversals when sediment motion may

not begin at the proper time; at these times, the flow patterns are often considerably different than at strength of flow. If more or less model sediment is in motion during flow reversals, the patterns of transport will be different for the volume transported during that interval. A common method of compensating for low model values of R_* is to prolong periods of high current velocities so that the percentage of time at low velocities is reduced.

Verification

38. Use of sophisticated theory to design a movable-bed model does not eliminate the verification process. Although theory can provide useful design guidelines, it cannot guarantee that the model will satisfactorily reproduce prototype behavior. Verification requires that a complex and unsteady set of prototype conditions of tides, waves, and sediment supply that are poorly defined (if they are defined at all) be modeled by a simplified set of model conditions. By choosing a theory, the modeler is able to develop scales for the important phenomena; but fortunate indeed is the modeler who has adequate, reliable prototype data to which the scales may be applied. In any case, a variable tide must normally be replaced with a simplified average tide, a spectrum of wave heights, periods, and directions with a few typical waves, and most wind effects must be neglected altogether. Then after the model is operated with these simplified conditions, the modeler must compare the results with prototype data that were taken for another purpose and that were altered by storms, dredging, and other occurrences.

39. This litany of the woes faced by the movable-bed modeler serves to emphasize that the modeler's art and experience are often as important as his science and that model results require careful interpretation. The interpretation must take into account limitations of the model in reproducing prototype behavior and accuracy of both model and prototype data. It must also be emphasized that model results cannot be interpreted too specifically--that a given volume of sediment will accumulate in a certain time or that a shoal will form in a particular spot. In short, a movable-bed model is an engineering tool whose limitations must be understood before its results may be profitably applied.

PART II: GALVESTON HARBOR ENTRANCE

Description

40. Galveston Harbor entrance is a controlled tidal inlet on the Texas coast (Figure 1) connecting Galveston Bay with the Gulf of Mexico. The inlet separates Galveston Island from Bolivar Peninsula. The Federal navigation channel through the inlet provides access between the Gulf of Mexico and Galveston Harbor, the Gulf Intracoastal Waterway, Texas City Channel, and Houston Ship Channel.

41. The entrance is protected on both the northeast and southwest sides by rubble-mound jetties. The north jetty extends into the Gulf of Mexico 25,907 ft* from Bolivar Peninsula and the south jetty is 35,900 ft long, though it extends only about 14,000 ft beyond the shoreline. A small-boat opening penetrates the north jetty about 8,000 ft from shore. Both jetties were completed prior to 1910 and have been repaired a number of times. At the time the model study was initiated (1960), the jetties were in moderate disrepair, with low sections and large voids that permitted currents and sediment to sweep through the jetties. During the period 1964 through 1967, most of the north jetty was rehabilitated; but at the recommendation of the model study, the outer 3,000 ft was allowed to deteriorate. During the same period, the outer 10,000 ft of the south jetty was rehabilitated.[9]

42. Prior to the model study the entrance channel approached the jetties from the southeast (Figure 2), turned westward near the north jetty and paralleled it for a short distance, then turned southwest toward Galveston Channel. The channel reaches are designated as the inner bar channel, outer bar channel, and approach channel as shown in Figure 2. Project design from 1950 to the time of the model study consisted of an 800-ft-wide by 36-ft-deep** inner bar channel and 800-ft-wide

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* A table of factors for converting U. S. customary units of measure to metric (SI) units is presented on page 7.

** Depths and elevations are referred to mean low tide (mlt), unless otherwise noted.

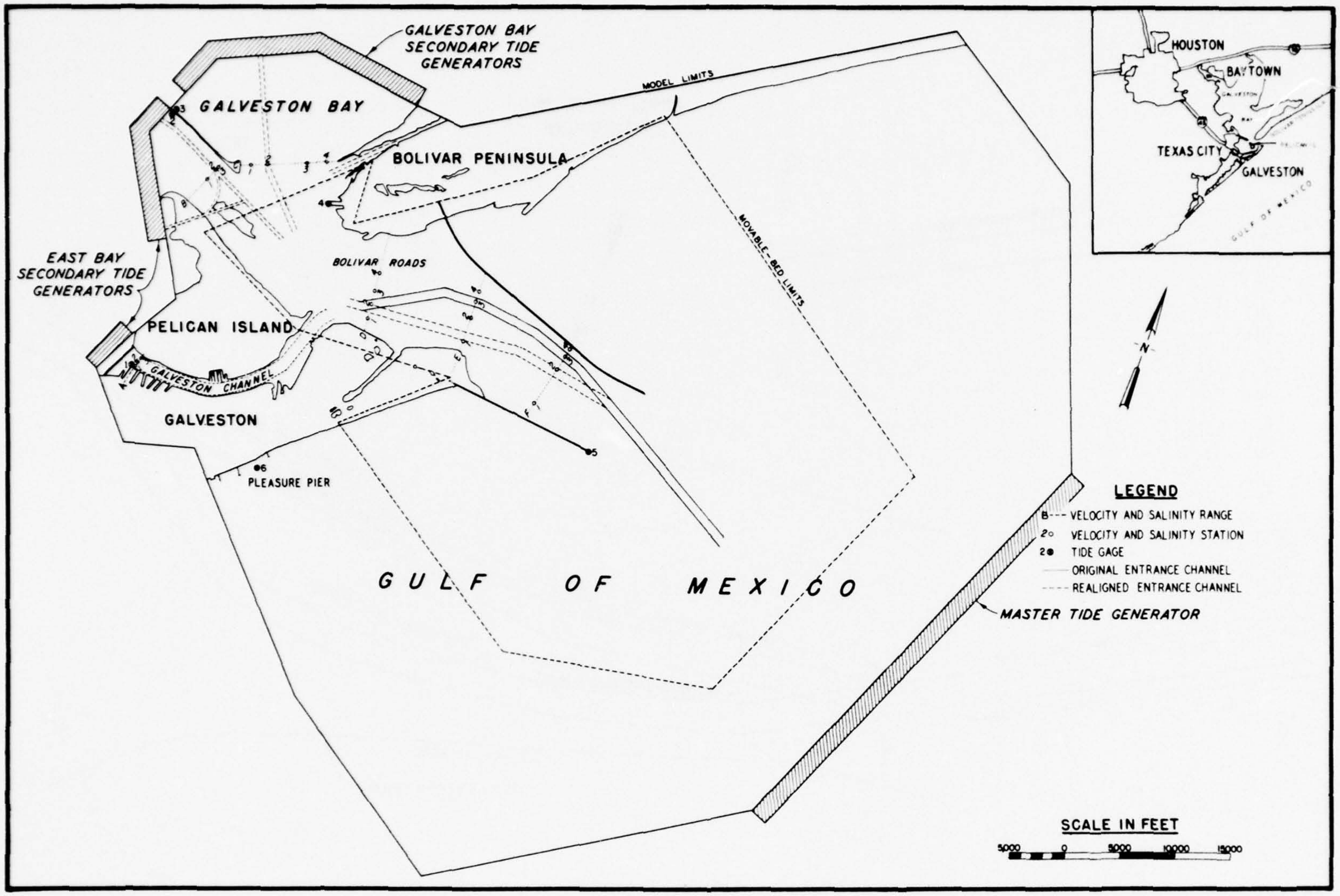

Figure 1. Location map and model limits

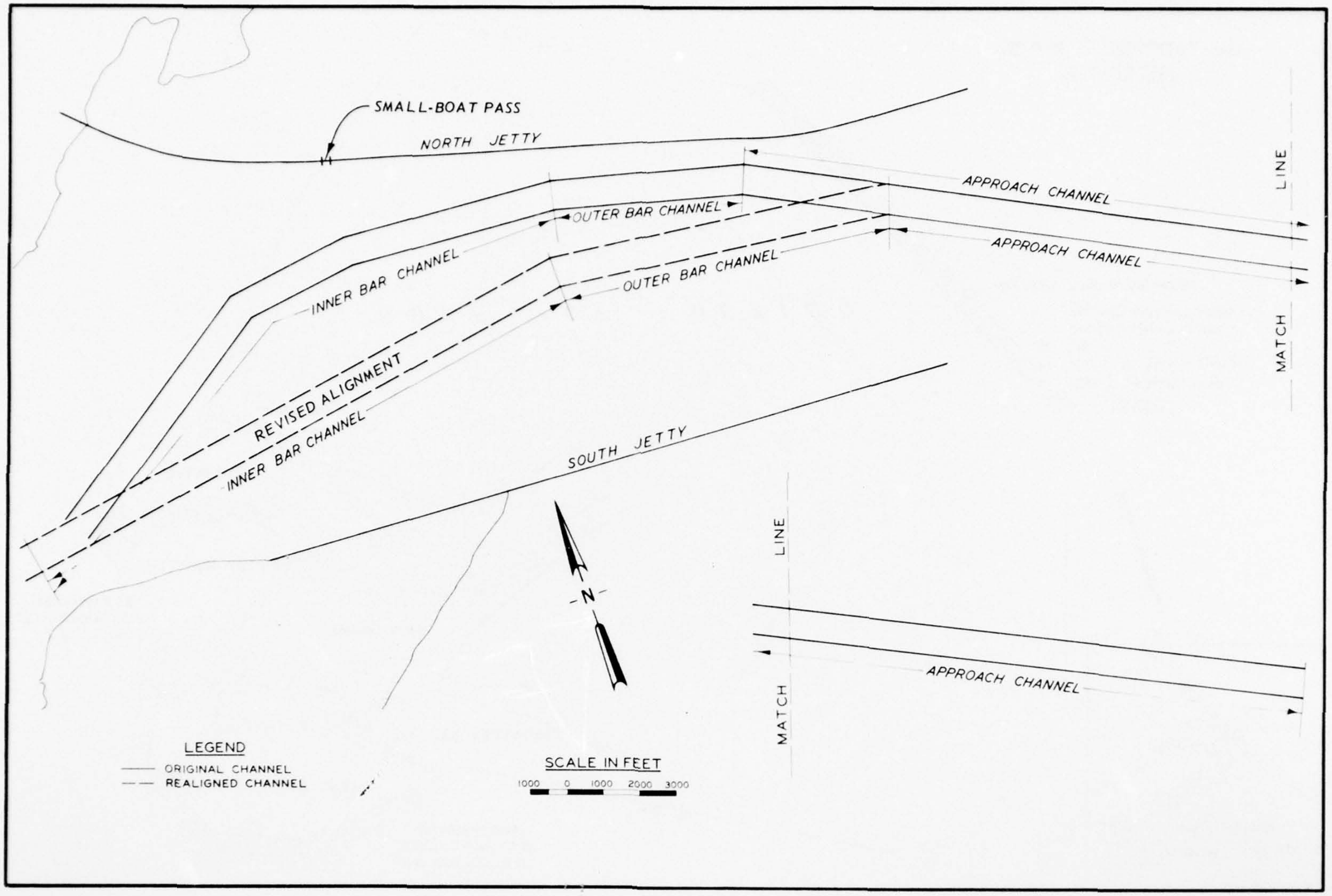

Figure 2. Galveston Harbor entrance channel realignment

by 38-ft-deep outer bar and approach channels; prior to 1950, the channels were 2 ft shallower. Following the model study, deeper channels (40 and 42 ft, respectively) were dredged along the revised alignment shown in Figure 2.

43. Sediments in the entrance channel are predominantly fine sands of the type found on the beach face. Bed samples collected in 1960[10] at various depths showed median grain sizes on the inner bar ranging from 0.004 to 0.7 mm and specific gravities of 2.64 to 2.69. Of 45 samples from the inner bar area, 64 percent had median grain sizes in the sand size range and 36 percent in silt and clay sizes. Only three samples in water less than 20 ft deep had a median grain size in the silt-clay range. Outer bar samples exhibited median grain sizes of 0.025 to 4.7 mm and specific gravities in the range 2.63 to 2.75. From a total of 36 samples in the outer bar area, 58 percent had median grain diameters of sand size or larger. Typical median grain sizes were 0.08 mm for the inner bar channel and 0.12 mm for the outer bar channel. Previous bed sample analyses[11] found the sand spit between the jetties to be 99 percent fine sand with a median size of 0.14 mm and the outer bar to consist of 90 percent fine sand with a median size of 0.15 mm. The inner bar samples had a median grain size of 0.12 mm and were 83 percent fine sand. Sediment found in the Galveston Channel near Pelican Island was 60 to 70 percent clay.

44. Tides at Galveston are predominantly diurnal but have a semidiurnal component during part of the lunar month. Mean tide range is 2.0 ft outside and 1.4 ft inside[12] the inlet. Galveston Bay has a surface area of about 459 square miles and a tidal prism estimated to be about 75,000 to 250,000 acre-ft for normal tides.[11] The tidal prism of the bay is shared by Galveston Harbor entrance and Rollover Pass, 20 miles northeast of Galveston. Barometric tides and wind setup and setdown can cause large variations in water-surface levels, even obscuring astronomical tides. Extreme water-level observations range from -4.3 ft mean sea level (msl)* to +12 ft msl.[13] Such large deviations from normal

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* 0.0 msl = 0.7 mlt.

water levels cause extreme variations in tidal prism as well and have the potential to alter the inlet configuration.

45. Maximum current velocities in the entrance channel usually range from 3 to 5 fps, although spring tide velocities greater than 7 fps have been observed.[13] Peak ebb current velocities are often greater than peak flood velocities, apparently due to a shorter ebb flow duration and ebb flow concentration.

46. Principal sources of freshwater inflow to the bay are the Trinity and San Jacinto Rivers. Annual average inflow from all tributaries is about 8700 cfs of which about 7000 cfs comes from the Trinity River.[13]

47. Salinity observations of the entrance in 1965 showed salinities ranging from 13.8 ppt at the surface and 25.8 ppt at the bottom during high freshwater flows to 32.2 ppt and 32.3 ppt at the surface and bottom, respectively, for low freshwater flows.[13]

48. Wind effects are an important factor in sediment transport as well as water levels in Galveston Bay. The prevailing wind directions are from the south and southeast, but strong northerly winds are frequent in the winter. Local waves and currents generated by the wind resuspend and transport large volumes of sediment within the bay. Winter storms called northers affect tides, currents, wave conditions, and sediment transport for several days. Northers begin by blowing strongly from the south, causing wind setup in the north end of the bay and setdown in the south end, just inside the inlet. This causes high flood flows through Bolivar Roads (Figure 2), until the setdown is compensated for and the general bay elevation is increased, which results in stored water in the bay. Then the winds shift to the south, causing setup in the south end of the bay and the stored water leaves the bay, causing high ebb velocities through Bolivar Roads. This rapid lowering of the water levels in the bay may cause heavy sediment transport into the inlet area. However, the high current velocities through the inlet may cause scouring, depending on the amount of sediment being supplied from the bay.

49. Net littoral transport in the vicinity of the inlet is

generally considered to be toward the southwest.[11, 14-16] Watson[16] calculates the gross littoral transport rate at Caplen, 17 miles northeast of Galveston, to be about 430,000 cu yd per year with a net transport of about 130,000 cu yd per year toward the southwest. At East Beach, immediately southwest of the inlet, he calculates a gross transport rate of only 120,000 cu yd per year and a net of about 20,000 cu yd per year toward the southwest. Watson notes that both gross and net transport computed volumes at East Beach may be low since the observation point for the wave data used is shielded from northeast waves by the south jetty. Estimates of transport rates for both locations show a gross transport rate three to six times the net transport.

50. A sand tracer study at Galveston Harbor entrance[17] found that sand from northeast of the jetty moved both through the north jetty small-boat pass into the inner bar channel and around the tip of the jetty into the outer bar channel. During the brief tracing study, material placed southwest of the inlet did not move into the entrance.

51. Table 2 shows frequencies of wave heights and periods occurring in deep water near Galveston. The bulk of the waves are rather short-period waves (less than 6 sec) between 1 and 4 ft in height, but there is a significant percentage (17 percent) of wave heights between 5 and 6 ft. Plates 1 and 2 show offshore wave period and height roses generated by hindcasting techniques.[19] The frequencies of occurrence shown in the roses are annual averages calculated for 1950, 1952, and 1954 for a location about 115 miles southeast of Galveston at latitude 27°58'N and longitude 93°52'W. According to these hindcasts, both sea and swell are predominantly from the south-southwest to east-southeast with swell, constituting about 10 percent of the wave frequencies, exhibiting strongly predominant directions between south-southeast and east-southeast.

52. Shoaling processes in Galveston Harbor entrance can be temporarily altered by tropical storms. Surges caused by the storms can result in wave erosion of coastal dunes, adding sediment to the littoral zone. High water levels may also cause overtopping of the jetties and high flow rates through the inlet. Waves generated by more

distant tropical storms can greatly increase the littoral transport rate and temporarily load the entrance with excess sand.

53. Hurricanes pass close to Galveston on an average of every 5 to 10 years, but tropical storms, including those that do not qualify as hurricanes, pass near the Texas-Louisiana coastal area much more frequently. Table 3 lists tropical storms and hurricanes occurring in the Gulf of Mexico during the period 1950-1973 and Plates 3-5 show the paths of storms that occurred during periods addressed by this study.

54. It has been reported[11] that the hurricanes of 1900 and 1915 that struck Galveston did not cause large changes in cross-sectional area of the inlet. The effect of Hurricane Carla (September 1961) on shoaling in the Galveston Harbor entrance channel was well documented by the U. S. Army Engineer District, Galveston,[20] and offers an insight into the effects of hurricanes passing close to the inlet. Carla crossed the Texas coast on 11 September 1961 near Port O'Connor which is about 120 miles southwest of Galveston. A maximum storm surge elevation of 9.3 ft msl was recorded at Galveston and maximum water-surface elevations of up to +15 ft msl occurred in Galveston Bay. Wave heights were not measured. A survey of the entrance channel within the jetties was made in June, 3 months before Carla, and another was made a month after the storm. Comparison of the pre- and post-Carla surveys (Plate 6) showed that approximately equal amounts of scour and fill occurred, with scour covering a somewhat greater area. Most of the shoaling occurred along the north jetty where depths decreased as much as 6 ft. Another shoal area was situated along the inside of the outer end of the south jetty. Shoaling on the inner bar suggests that a substantial amount of sand passed over or through the nearshore end of the north jetty.

55. The Galveston Harbor entrance channel is dredged annually, usually during the fall months, by Government hopper dredges. Dredged volumes for the period 1953 to 1973 are shown in Table 4. The average annual dredging volume prior to enlarging and realigning the entrance channel in 1965-1968 was 1,240,000 cu yd.

56. Prior to realignment, the entrance channel required

substantial dredging as shown in Table 4 and experienced scour at the toe of the north jetty where the outer bar channel paralleled it. In addition, its junction with the Houston Ship Channel was a sharp turn that was difficult to navigate.

Construction of Realigned Channel

57. Based on the results of the movable-bed model study, the entrance channel was deepened and realigned to a more direct route to the Gulf of Mexico (Figure 2), easing the sharp bend at the inner ends of the jetties and shifting the channel an appreciable distance away from the north jetty in the area where undermining by tidal currents threatened. The entrance channel was deepened 4 ft over its entire length to project depths of 40 and 42 ft, respectively, for the inner and outer bar channels. An anchorage basin was also constructed between the new and the abandoned channel with a depth of 34 ft covering 2 square miles (Figure 3).

58. A procedure for constructing the realigned channel was developed by WES and the Galveston District. This construction schedule was estimated to require approximately 2 years to complete. A model test incorporating this procedure was conducted covering 2 model years of construction and continuing for 6 years thereafter. The prototype construction sequence was very similar to that followed in the model; however, the time required for construction was approximately 3 years. Construction of the channel realignment began in December 1964 and was completed in October 1967. Construction of the anchorage basin required an additional 17 months.

59. The prototype construction sequence is shown in Figure 3. The volumes dredged during this sequence of construction are presented in Table 5. The first phase of the construction sequence was to excavate the southern half of the realigned inner and outer bar channels. During the second phase, the approach channel was deepened concurrently with excavation of the northern half of the inner and outer bar channels. Finally, the anchorage basin was dredged.

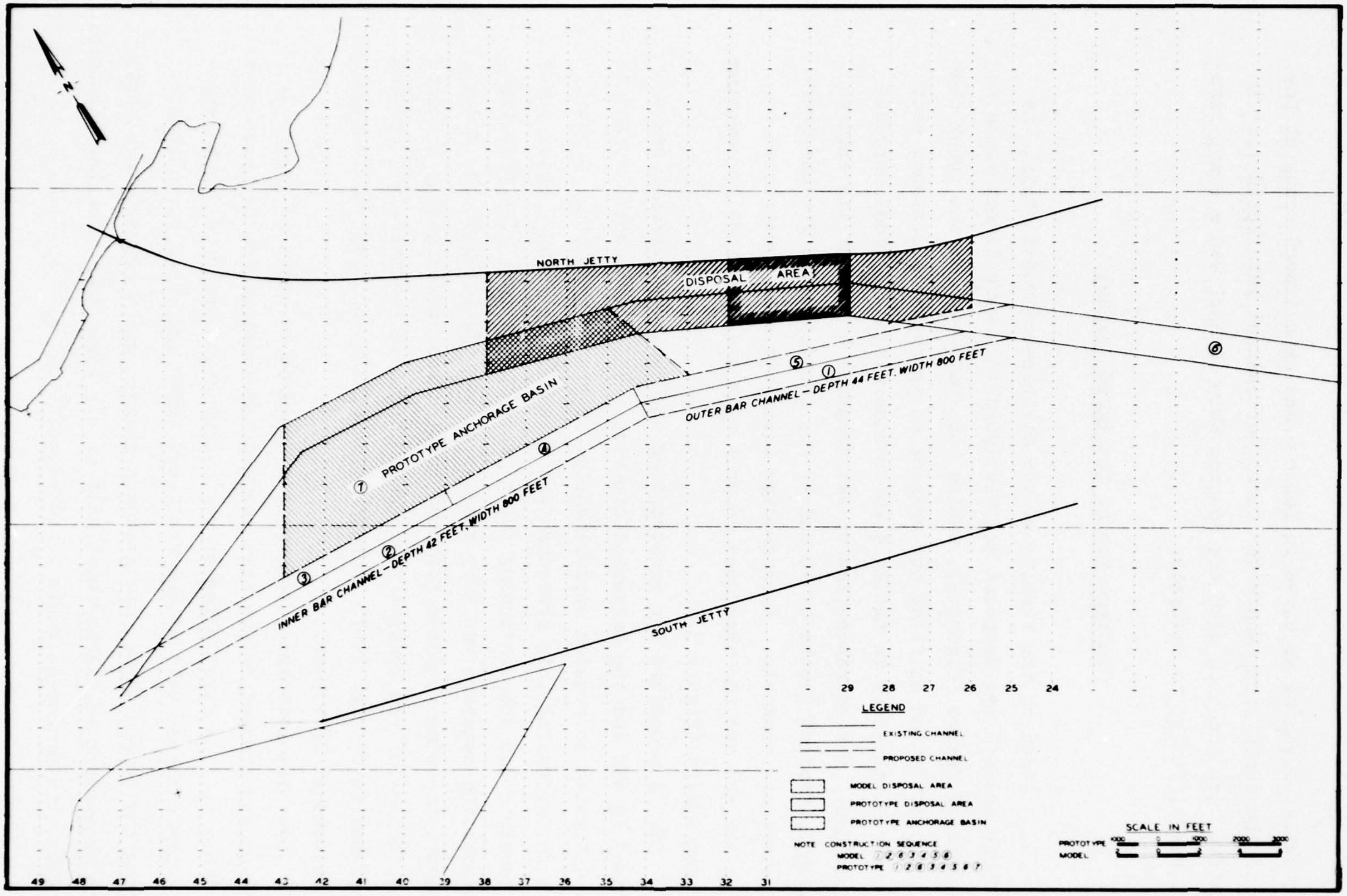

Figure 3. Construction procedure

60. During the first 8 months, 3,608,500 cu yd was removed while excavating the southern half of the inner and outer bar channels and partially deepening the approach channel. This material was deposited either on land or in the sea disposal area well outside the jetties. For the remainder of the construction sequence (second phase), the partially completed new channel was opened to ship traffic and a portion of the old channel alongside the north jetty was used as a disposal area. During the second phase of construction, 12,931,400 cu yd of material was dredged from the realigned channel and 4,790,500 cu yd was dredged from the anchorage basin. Of this 17,721,900 cu yd dredged during the second phase, 5,845,100 cu yd was deposited in the abandoned channel adjacent to the north jetty. This disposal area was used to alleviate the scouring at the toe of the north jetty by tidal currents and to maintain a constant crosssectional area between the jetties.

61. During the prototype construction period, 16,540,000 cu yd of material was dredged from the realigned navigation channel and 4,791,000 cu yd was dredged from the anchorage basin. Of this construction dredging total of 21,329,900 cu yd, 5,845,100 cu yd of material was deposited in the old channel.

62. Following the completion of channel realignment, maintenance dredging was performed each year. The dredging usually began in November or December and was concluded early in the following year, between February and April. This pattern held until the sixth year after the completion of construction. In January 1974, the hopper dredge *MacKenzie* sank in the entrance channel while dredging, partially blocking the channel. Emergency dredging operations were required to bypass the sunken dredge. As a result, maintenance dredging figures for that year were not determined. That occurrence marks the end of the prototype data period used for this postconstruction verification study.

Data Collection

63. Prototype data collection was accomplished by the Galveston District at intervals over the long period involved in this study. The

data were not collected specifically for this study but rather as routine investigations of the condition of the Galveston Inlet area and navigation channel. The data were supplied by the Galveston District upon request by WES.

64. Several types of prototype data were used in this study. Annual dredging volumes for 1950 to 1959 were obtained from the Annual Reports on Civil Works Projects, OCE.[9] Dredging volumes for 1953 to 1961 were supplied WES by the Galveston District at the time of the original model study. Dredging volumes from 1960 to 1973 were obtained from the hopper dredge operations monthly report sheets and confirmed by the volumes reported in the OCE Annual Reports.

65. Before and after each postconstruction dredging operation, surveys of the entrance channel were made. These soundings were conducted by simultaneously employing the triangulation system for horizontal control and the fathometer strip chart recorder for vertical control. The accuracy of the control used during these surveys is dependent on many variables. Vertical control is affected by fathometer accuracy; vessel loading and attitude; wave action; vessel rolling, heaving, and pitching; correction for tidal fluctuation; and water temperature and salinity. Horizontal control accuracy is dependent on angular uncertainty, distance between the transit and boat, speed of the boat, and human error in reading the transit. With reasonable care, the error in vertical control can be reduced to the effects of wave action and vessel motions. For average wave conditions, the vertical control may be assumed to be accurate within ± 1 ft.

66. At intervals over the period covered in this study, comprehensive hydrographic surveys were made of the vicinity of Galveston Inlet, covering the area between the jetties and the surrounding offshore areas. These surveys utilized an automatic recording tape system in connection with electronic positioning equipment. These surveys were used to determine the relative zones of shoaling and scouring in the overall area between the jetties. By using this system, the horizontal control is believed to be within 1 m, the best that can be attained at present. With this system, however, the problems involved in vertical

control are the same as with the triangulation system.

67. The potential error in computing shoaling volumes from the hydrographic data used in this study is difficult to estimate. If the error in an individual depth reading is accepted as ±1 ft, the average error over the entrance channel should be less than 1 ft unless a systematic error occurs. Such a systematic error might be an incorrect adjustment for tidal stage. If the average error were as great as 1 ft, it would have little impact on scour-and-fill analyses that look for several feet of change but would drastically affect shoaling volumes. For example, the bottom of the entire entrance channel covers about 40×10^6 sq ft, and an average depth error of 1 ft would constitute a shoaling volume error of 1.5×10^6 cu yd. This is equivalent to a year's dredging volume. Even a 0.1-ft average error would constitute a 10 percent error.

68. An additional source of potential error is contamination of individual surveys by seasonal variations in shoaling patterns and volumes. This report deals only with average annual shoaling volumes which should experience minimal effect from seasonal variations. Seasonal variations could affect bed condition maps generated from soundings obtained at different times of the year, but it is believed that such seasonally induced changes would be less than those due to singular events such as storms that might affect bed configuration for a year or more.

PART III: THE MODEL

Description

69. The Galveston Harbor entrance model was a combination fixed- and movable-bed model reproducing Bolivar Roads, a small portion of Galveston Island and Bay, and a portion of the Gulf of Mexico (Figure 1). The movable-bed portion of the model, shown by the dotted line in Figure 1, included the jetty channel, a short section of beach on either side of the jetties, and offshore hydrography to the 50-ft depth contour. The fixed-bed portion of the model was molded in concrete and the movable-bed portion, in crushed coal.

70. The model jetties were constructed of gravel mortar. At locations along the breakwater where prototype surveys had indicated a large surface gap, the model jetty was constructed with a similar gap. Voids below the waterline and breakwater porosity were not reproduced in the model.

71. Model length scales were 1:100 vertically and 1:500 horizontally. The resulting scales for hydrodynamic phenomena can be computed from Table 1. Scales for sediment transport are discussed in this section under the heading of scale effects.

72. The model sediment was crushed coal (angle of repose about 33 deg) with a specific gravity of 1.4, a median grain size of 1.4 mm, and a grain size range of 0.1 to 5.0 mm. The median grain size was adjusted to that which resulted in no bed ripples. Pronounced bed forms were not observed in the model.

73. Fresh water was used in the model throughout the tests.

Appurtenances

74. Four tide generators at locations shown in Figure 1 maintained proper tidal elevations and flow rates at the model's water boundaries.

75. Waves were generated in the model by a 100-ft-long

plunger-type wave generator that was moved to provide the desired direction of wave approach. Adjustment of stroke and angular speed of the plunger permitted variation in wave height and period.

76. The movable-bed portion of the model was molded to its initial configuration for each test by means of sheet metal templates suspended from elevated grade rails. Soundings of the bed surface were taken by means of horizontally graduated guide rails and a vertically graduated sounding rod with a hinged pad at the bottom to prevent penetration into the coal while sounding. The soundings were obtained at 0.4-ft (200 ft prototype) intervals along ranges separated by 2.0 ft (1000 ft prototype) as shown in Figure 3.

Hydraulic Verification

77. The hydraulic verification procedure involved adjusting the master tide generator to reproduce observed prototype tidal elevations at the Pleasure Pier gage (Figure 1), then adjusting the secondary tide generators to properly reproduce observed prototype tides at sta 1-5 and velocities at sta A-1, B-2, C-2, and F-3. Results of the hydraulic verification are shown in Plates 7-9.

Shoaling Verification

78. Verification of shoaling in the model was based upon dredging records for the period 1957-1961 and comprehensive hydrographic surveys of 1950 (Plate 10) and 1960 (Plate 11). The verification process is discussed in Reference 2.

79. Model operation for final shoaling verification is illustrated in Figure 4 and described below. A mean tide (2.1-ft range) was maintained at Pleasure Pier, but current velocities were increased 35 percent over mean tide values. The sequence of operations was as follows:

- a. Beginning at high water, the tide alone was produced for a half cycle to low water.
- b. Waves (paragraph 81) were produced for one cycle together with the tide.

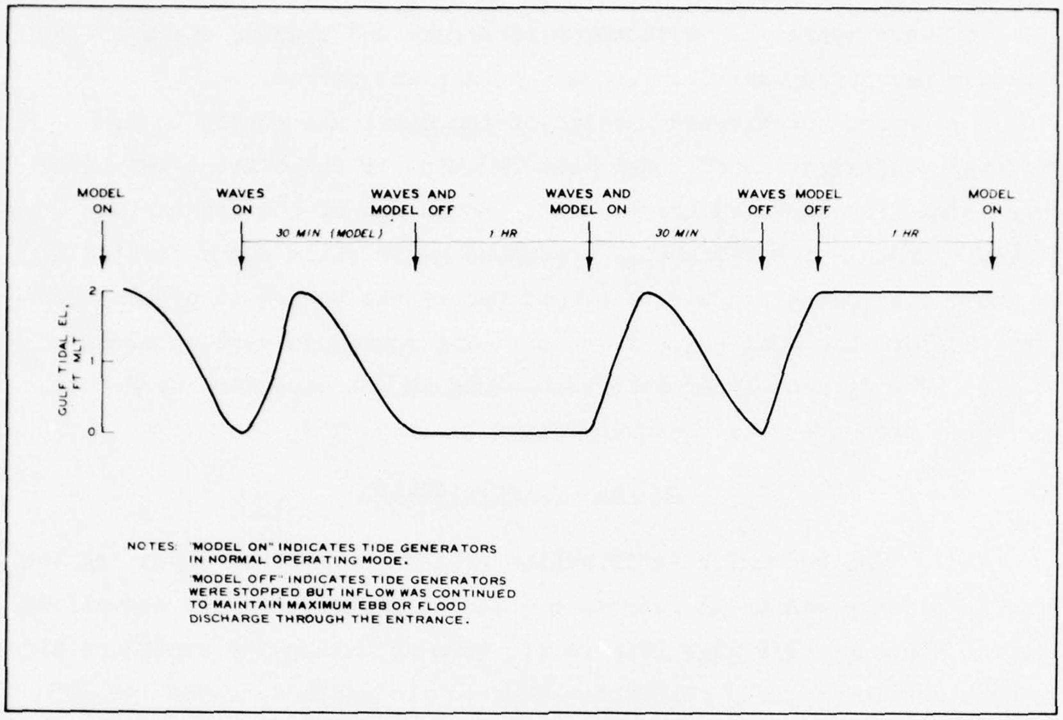

Figure 4. Model operating technique for movable-bed verification

c. At the second low water, waves and tide were stopped and maximum ebb velocities were maintained for 1 hr (model) by holding a constant head across the inlet.

d. Tide and waves were resumed for one cycle. At next low water, waves were stopped and tide was continued to high water.

e. At high water, the tide was stopped and maximum flood velocities were maintained for 1 hr (model).

f. The tidal operation sequence was repeated (a through e).

Each sequence (a through e) required about 3-1/2 hr. At the end of two such sequences (7 hr), model operation was stopped altogether and the navigation channel was dredged. The verification process consisted of repeating the pattern (two sequences and dredging) seven times, representing a prototype period of 7 years.

80. Dredging in the model during verification tests and subsequent plan tests consisted of dredging only those areas where the depth

was shallower than the project depth. When dredged, these areas were deepened to 4 ft greater than design depth (2-ft overdepth and 2-ft advance maintenance).

81. Wave direction, period, and height were adjusted until sediment movement in the outer bar was as desired. The wave used in the final verification was from S37°E with a model period of 0.77 sec. More oblique wave angles from both sides of the inlet were tried but insufficient movement of the model bed was observed at other angles. Model wave height was not recorded but was estimated to be about 0.05 ft. These characteristics correspond to a prototype wave of 7.7-sec period and 5-ft height according to the scale ratios of Table 1, using refraction as the controlling factor in wave modeling.

82. Although the portion of the model in which the wave generator was placed was about 1.2 ft deep (120 ft prototype), its scaled distance offshore corresponded to a location 50 to 60 ft deep in the prototype. Thus the verification wave could be expected to have experienced some refraction and some height change prior to its arrival at the wave generator location. Because of the wave crest's orientation (nearly parallel to the coastline), very little refraction would have occurred if the wave had originated in deeper water. Wave shoaling computations indicate that the deepwater wave height in absence of refraction would have been about 10 percent higher than the wave occurring at the wave generator location.

83. Dredged volumes for the period FY 1953 through FY 1961 were worked up for the navigation channel and provided by the Galveston District, for use during shoaling verification. In the original verification, the period 1957-1961 was used for comparison with model results. The dredging volumes for that prototype period and model scaled volumes for a 7-year period are presented in Table 6. Note that these volumes differ from those in Table 4. For the verification tests, the dredged volume for the outer bar channel and approach channel were combined into a single figure for the outer bar channel due to having no finer breakdown of prototype volumes. The tables show the model and prototype dredged volumes for the inner and outer bar channels for each year and then an average annual rate.

84. The last row of numbers in the top and bottom portions of Table 6 gives the maximum variations in annual dredging for the average values. In the prototype, the annual rate will vary according to the natural variations in shoaling rate plus artificial variations due to dredge availability, funding levels for maintenance operations, and use of allowable overdepth and advance maintenance. Variation in model values will be due to imprecision in the dredging process and minor changes in the shoaling rate due to changing sediment supply from the undredged portions of the model. The 1957-1961 prototype period was used for comparison with model values for shoaling verification.

85. The model average dredging volumes compare fairly well with those of the prototype. Distribution of dredging between inner and outer bar channels was roughly the same in model and prototype, although the model volumes were about 24 percent less than those of the prototype.

86. Prototype bed changes for the verification period, developed from Plates 10 and 11, are shown in Plate 12 and those for the model in Plate 13. These two maps reveal that the model reproduced some patterns but not others. Both maps show a moderately large shoal forming at the inner end of the inner bar channel with the model shoal displaced somewhat seaward of its location in the prototype. Similarly, both show a large scour zone between the channel and south jetty although in the prototype it is closer to the jetty than in the model. Obvious differences in the model (Plate 13) are the shoal just inside the south jetty and the lack of slight reductions in depth outside the jetties.

Base and Plan Tests Description

87. The basic model operating procedure for base and plan tests was identical with that used for verification. The testing procedure, however, was lengthened for the base tests to represent a 12-year period. The first 8 years had annual dredging to restore project channel depths. After the eighth year, about 3,000,000 cu yd of sediment was placed between the channel and the inner end of the south jetty to

simulate storm deposition. The model was then operated for an additional 4 years, with maintenance dredging at the end of each year.

88. For the base test, the movable-bed section was molded to the configuration of the 1960 survey except for the navigation channel, which was dredged along the existing channel alignment to project dimensions. Dredged material was placed in the prototype disposal area 3 miles offshore of the south jetty.

89. The recommended plan, designated plan 2, was constructed as shown in Figure 2 (with the construction sequence described in paragraph 59). Areas outside the channel initially were molded to the 1960 condition. The existing channel was dredged to project dimensions and the realigned inner and outer bar channels were dredged to 800 ft wide by 42 ft deep and 44 ft deep, respectively. The approach channel was dredged to 800 ft wide by 44 ft deep along its previous alignment; deepening the channel by 4 ft required extension of the approach channel farther offshore, increasing its length by about 30 percent. A portion (4,000,000 cu yd) of the annual dredged volumes during the plan test was placed in a disposal area along the inside of the north jetty and in the abandoned reach of outer bar channel as shown in Figure 3. The proposed channel realignment placed the navigation channel along an apparent meander channel through the inlet.

90. Five channel realignment plans were tested in the model. Plan 2 was determined to be the best of the five and was selected for construction. A repeat test of plan 2 was performed to check model repeatability and to serve as a base test for subsequent testing. Comparisons of the initial and repeat test results are presented in Table 7. Substantial variation occurred among yearly volumes and the 8-year average changed by about 15 percent.

91. With the plan 2 channel realignment installed in the model, supplemental studies were conducted of construction procedures for the realigned channel, jetty rehabilitation, use of dredged material disposal area, dredging techniques, and anchorage basins.

92. Personnel of WES and the Galveston District developed the sequence for construction of the channel realignment (as described in

paragraph 59 and Figure 3) to be tested in the model. Construction procedure tests involved dredging the realignment channel in increments over a 2-year period. At the beginning of the test, the south half of the realigned inner and outer bar channels was dredged to project depth and the dredged material was removed from the model. The approach channel was dredged to a depth of 40 ft. After 1 year of model operation, the north half of the realigned inner bar channel was also dredged to project depth and maintenance dredging was performed on the previously dredged sections. Part of the dredged material was removed from the model and part was placed in the abandoned outer bar channel. After an additional half year of operation, the north half of the realigned outer bar channel was dredged to project depth and maintenance dredging was performed on previously dredged reaches. All dredged material in this operation was placed in the abandoned outer bar channel. After a second half year of operation, the approach channel was dredged to project depth (44 ft) and maintenance dredging was performed, with dredged material again being placed in the abandoned outer bar channel. The model was then operated for six additional years, with maintenance dredging at the end of each year.

93. Tests were also conducted to determine the effects of permitting the outer 3000 ft of the north jetty to deteriorate. The model was operated for 2 years with the plan 2 channel installed; then the jetty was degraded to an elevation of -12 ft mlt. The model was then operated for 6 years as described in the base test.

Scale Effects

94. Determination of hydraulic scale effects in the model is relatively straightforward. Model and prototype had average Reynolds numbers of about 3×10^3 and 3×10^6, respectively, both well in excess of values (about 500 to 1000) at which viscous flow may occur. Model Reynolds numbers did not approach the viscous range until velocities dropped to about 0.05 fps (prototype scale) in the areas of interest. This occurred for a very small fraction of the tidal cycle, so hydraulic

scale effects due to viscous effects can be considered negligible.

95. The combined effect of raising model velocities by 35 percent and prolonging maximum velocities in the verification tests would make the model-to-prototype scale ratio for the average tidal current velocity about 1:5.5 rather than the Froudian 1:10. However, Plate 9 shows that the model velocities were somewhat low in the hydraulic verification test. Average and maximum velocities for model (hydraulic verification) and prototype are presented in Table 8 for sta B-2, C-2, and F-3; locations of these stations are shown in Figure 1. These comparisons show that increasing model velocities for the shoaling tests actually would improve prototype-to-model hydraulic agreement. The mean prototype-to-model average velocity ratio for the three stations was 1.3 for hydraulic verification, suggesting that the increase in model velocities actually resulted in more accurate model reproduction of prototype velocities during shoaling verification. Computation of average velocities for model (shoaling verification) and prototype reveals that the shoaling verification velocity scale ratios were about 1:7 for flood velocities and 1:9 for ebb velocities.

96. Using the relations given by Table 1, the scale ratio for effective roughness size should be 1.25:1 for the Galveston model. In the model, where there were few bed forms, the effective roughness may be assumed to have been approximately equal to a representative grain size. The prototype bed almost certainly had bed forms, resulting in a roughness dimension somewhat greater than the grain size so it may be assumed that k_{sr} was less than the d_{50} scale ratio which varied from about 12:1 to 18:1 through the inlet. A reasonable estimate for the actual k_{sr} would be about 5:1.

97. The 5-ft, 7.7-sec wave used in the verification tests appears to have been a reasonable choice. It was somewhat higher and longer than a typical wave at the site (Table 2, Plates 1 and 2), but it may well have been close to a representative size for significant sediment transport. Judging from the offshore wave roses and a predominant littoral transport toward the south, the south-southeast direction of the verification wave may have been somewhat too far to the south. The

primary difficulty with using a single representative wave is that various water depths have different typical wave conditions for sediment transport and fluctuations in littoral transport will not be reproduced.

98. The verification wave direction resulted in a refracted wave that reached the approach and outer bar channels without significant diffraction. The inner bar channel experienced a diffracted wave; however, since the diffraction time scale is dependent upon the horizontal scale rather than the vertical scale, the model wave was diffracted as if it had a period of about 17 sec (prototype). With a 7.7-sec wave the model wave height experienced in the region of the inner bar channel would therefore be somewhat larger than that in the prototype.

99. If sediment in the entrance channel is characterized as having median grain sizes of 0.08 mm and 0.12 mm for the inner bar channel and outer bar channel, respectively, and if it is assumed that no significant sorting of sediments occurred in the model, then the sediment grain-size ratio was about 18:1 for the inner bar channel and 12:1 for the outer bar channel. The no-sorting assumption is probably a poor one, and it is possible that sorting lowered both these ratios.

100. Using a prototype sediment specific gravity of 2.65-2.67, the model-to-prototype scale ratio for the submerged weight of the sediment was about 1:4.2. This ratio and the sediment size ratio given in the preceding paragraph are compared in Table 9 with the values resulting from several equations presented in PART I of this report. Equation 7 would result in a reasonable sediment size but the specific gravity would be about 1:02, which might be impractical because of the tendency of small, light particles to float. Assuming the use of sand in the model ($\gamma_r' = 1$), Equation 9 suggests using a rather coarse sand when transport rates are high. In contrast to Equation 7, Equation 8 results in a fine model sediment grain size of 0.22 mm and specific gravity of about 1.4. Such a fine sediment might also tend to float. Although Equations 7 and 8 result in strikingly different model sediments, both would have moved more easily than the crushed coal used in the Galveston Harbor entrance model.

101. Values of Δ_{F_*} and Δ_{R_*} can be computed using the actual

scale ratios for velocities and sediment characteristics given in the preceding paragraphs. For tidal currents, the average value of Δ_{F_*} ranged from about 0.01 to 0.04; in contrast, Δ_{F_*} due to waves was about 0.4 for an assumed $k_{sr} = 5:1$. The obvious effect of these low values would be to require an exaggerated time scale to obtain sediment movement in the model equivalent to that of the prototype. It is probable that different time scales would be required in the inner bar channel, where tidal currents would tend to dominate the sediment transport; the outer bar channel, where both tidal currents and waves would be important; and outside the jetties, where waves would dominate.

102. Computation of a particle Reynolds number scale factor for transport by waves yields a Δ_{R_*} value of about 12 for the model conditions and assumed $k_{sr} = 5$. This value of Δ_{R_*} is quite high for a factor that would ideally be equal to 1. However, in areas of vigorous wave transport, incipient sediment motion and thus the value of Δ_{R_*} is of considerably lesser importance than Δ_{F_*} . For Δ_{R_*} due to tidal currents alone, using Equation 7 for the shear velocity ratio and the actual average velocity scale ratios given in paragraph 95 and Table 8 yields Δ_{R_*} values in the range of 3 to 6. In areas where tidal currents dominated the transport process, Δ_{R_*} is of greater importance than where waves and currents combine, since near times of slack water incipient motion may become significant to the overall sediment movement.

Accuracy of Model Measurements

103. Accuracy of model soundings is highly dependent upon the skill of the person making the sounding, but such measurements are considered to usually be accurate to within ± 1 ft (prototype), which is the same accuracy that has been assumed for the prototype. Dredged volumes were measured to the nearest 0.01 cu ft, which corresponds to about 9000 cu yd prototype volume. Repeatability of model average dredged volumes was assumed to be no closer than ± 15 percent based upon the results in Table 7.

104. Current velocity and tidal elevation measurement accuracies

do not directly affect the results of this study, but their accuracies were ±0.2 fps (prototype) and ±0.1 ft (prototype), respectively.

105. The model wave period and height described here are approximations based upon laboratory notes. Since simulation of a specific wave was not intended, these measurements were not made precisely; an indication of their approximate magnitude was sufficient.

PART IV: RESULTS

106. The model test data used for the majority of the analyses presented in this report are from the construction procedure test for the plan 2 realigned channel that was constructed in the prototype. Unless stated otherwise, that test is the source of the model data presented.

107. These results are presented in two basic forms--computed sediment volumes and bed hydrographic conditions. In the first four sections of PART IV, dredged volumes are analyzed by examining reported dredged volumes, volume changes computed from hydrographic surveys, dredged volumes adjusted for dredging vagaries, and computed dredging requirements based upon Galveston District guidelines. The next four sections present detailed bed conditions and bed changes in the navigation channel and in the overall inlet bed. The last section in PART IV is an analysis of tropical storm effects on the inlet.

Reported Dredged Volumes

108. The dredging volumes from the model base and plan 2 tests conducted without the construction procedure are shown in Table 10. These results are presented for the inner bar channel, the outer bar and approach channels combined, and the total entrance channel. The data show the primary reasons for selection of the plan 2 channel for construction in the prototype. For essentially no change in the annual maintenance dredging requirements after the first 2 years, a safer and deeper navigation channel is maintained. Also, the dredging distribution is shifted farther gulfward with the plan 2 channel. The data show the plan 2 channel had high shoaling rates for the first 2 years of the test, after which the dredging averaged only 812,000 cu yd, approximately the same as that for the base test.

Direct comparison

109. The dredging volumes that were reported by the Galveston District and the volumes removed from the model navigation channel

during the first 6 years after completion of channel realignment are presented in Table 11. In this table, the construction procedure was incorporated in the model test of plan 2. The validity of a direct comparison of model and prototype dredging volumes can be questioned due to irregularities in prototype dredging. These are discussed in paragraph 127.

110. The model test predicted that there would be no maintenance dredging required in the inner bar channel with an average of 300,000 cu yd (30 percent) and 711,000 cu yd (70 percent) of dredging annually for the outer bar and approach channels, respectively. This total annual dredging requirement of 1,011,000 cu yd predicted by the model test compares poorly with the 2,098,000 cu yd prototype average annual dredging experienced in fiscal years 1969 through 1973. No prototype dredging data were available for FY 1974 (the sixth year after construction) due to the sinking of the hopper dredge *MacKenzie*. The prototype distribution of dredging was 32 percent (671,000 cu yd) in the inner bar channel, 18 percent (369,000 cu yd) in the outer bar channel, and 50 percent (1,058,000) in the approach channel.

111. The maximum variation in the total annual dredging in the model was from a low of 593,000 cu yd (41 percent less than the average) to a high of 1,700,000 cu yd (71 percent greater than the average). The prototype variation in the annual dredging was from a low of 1,258,000 cu yd (40 percent less than the average) to a high of 3,150,000 cu yd (50 percent greater than the average). These variations are of the same degree; however, the times of occurrence of the extremes are not the same. The model test indicated a maximum dredging in the first year after completion of construction, while the prototype dredging the first year was the lowest for the postconstruction period.

Indirect comparison

112. The model data from Table 10 are summarized in Table 12 and compared with the prototype data from Tables 6 and 11. This comparison is presented to show the relative changes caused by the channel realignment in model and prototype. Prior to channel realignment the model inner bar channel required 31 percent of the total annual dredging, while the prototype inner bar channel dredging was 38 percent of the total.

For the realigned channel the model predicted the inner bar channel would require virtually no maintenance dredging, whereas the prototype inner bar dredging was 32 percent of the total.

113. The relative model prediction for the combined outer bar and approach channels was a 94 percent increase in dredging requirements with channel realignment. The prototype increase in dredging was also 94 percent for the outer bar and approach channels.

114. For the entrance channel as a whole, the model predicted an increase in annual maintenance dredged volume of 44 percent while the prototype channel actually experienced a 77 percent increase.

Hydrographic Volume Changes

Between dredgings

115. The hydrographic volume changes in the channel for model and prototype that occurred during the periods between dredging operations are presented in Table 13. The volumes of scour and fill are given as well as the net change for each channel section. The volumes were computed from the areas of scour and fill in vertical cross sections at 400-ft intervals along the channel center line.

116. The model inner bar channel scour averaged 324,000 cu yd annually, while the prototype scour averaged only 63,000 cu yd. Fill in the inner bar channel between dredgings averaged 54,000 cu yd and 1,068,000 cu yd annually for model and prototype, respectively. These average scour-and-fill volumes gave average net changes of 270,000 cu yd of scour for the model inner bar channel and 1,005,000 cu yd of fill for the prototype inner bar channel each year between dredging.

117. The outer bar channel average scour between dredgings each year was 112,000 cu yd in the model and 45,000 cu yd in the prototype. The average amounts of shoaling were 204,000 cu yd in the model and 489,000 cu yd in the prototype; thus, the net hydrographic change between dredgings in the outer bar channel averaged 92,000 cu yd of fill in the model and 444,000 cu yd of fill in the prototype.

118. In the approach channel the average scour volumes for model

and prototype were 234,000 cu yd and 74,000 cu yd, respectively, each year between dredging operations. The shoaling during the periods between dredgings averaged 308,000 cu yd in the model and 1,611,000 cu yd in the prototype approach channel. These volumes of scour and fill gave an average net change in the approach channel of 74,000 cu yd and 1,537,000 cu yd of fill for model and prototype, respectively.

119. The total net hydrographic change between dredgings averaged 104,000 cu yd of scour for the model, with a variation from a net scour of 630,000 cu yd to a net fill of 277,000 cu yd. This net scour for the entire channel is due to the large volumes of scour experienced in the inner bar channel that dominate the figures. The prototype average net change between dredgings was 2,986,000 cu yd of fill, varying from 1,095,000 to 4,623,000 cu yd of fill.

120. The model averages for the 6 years show that scour volumes and fill volumes are of the same order of magnitude in the outer bar and approach channels; but that in the inner bar channel the scour is large and the fill is small, resulting in a large net scour in the inner bar channel and a small net scour in the entire entrance channel. In contrast, throughout the entrance channel the prototype scour is small relative to the amount of fill, giving a very large net fill. The model average annual scour is 3.7 times greater than the prototype scour and the model fill averaged about one-sixth that of the prototype.

<u>During dredging</u>

121. The hydrographic volume changes in the channel that occurred during model and prototype dredging operations are presented in Table 14. The scour (including dredging), fill, and net change are presented in the table for each channel section. Also shown are the overdepth and underdepth that existed in model and prototype at the end of the dredging operations. For this report overdepth is defined as that volume of material representing areas of depth greater than project depth. It is a condition of the channel relative to project depth and does not necessarily correspond to overdredging volumes. It may be thought of as the shoaling volume required to bring the channel up to project depth. Underdepth is defined as that volume of material that is above project

depth. These volumes represent channel conditions shown by after-dredging surveys.

122. The average values show that the magnitudes of the changes occurring in the model were very low relative to the prototype changes. The average model scour (425,000 cu yd) was only 14 percent of the prototype average scour (3,138,000 cu yd) for the entire channel. The model average fill (40,000 cu yd) occurring during dredging was only 18 percent of the prototype shoaling during dredging (218,000 cu yd). This would be expected for the shoaling volumes since the model was not operated during the dredging operation. The average net change was low for the model (385,000 cu yd of scour) relative to the prototype average net change (2,920,000 cu yd of scour), reaffirming that model dredged volumes were low.

123. The overdepth and underdepth volumes for the navigation channel were determined from the after-dredging surveys. These volumes are computed based on a project depth of 42 ft for the inner bar channel and 44 ft for the outer bar and approach channels.

124. The average overdepth for the entire channel after dredging was 1,252,000 cu yd and 2,935,000 cu yd for model and prototype, respectively. For both model and prototype, the inner bar channel was the section with the largest average overdepth, 958,000 cu yd and 1,508,000 cu yd, respectively.

125. The underdepth for the entrance channel as a whole averaged 1,212,000 cu yd in the model and 989,000 cu yd in the prototype. The largest percentage of the underdepth in both model and prototype was in the approach channel, with 770,000 cu yd and 676,000 cu yd, respectively.

126. It is interesting that the model average overdepth (1,252,000 cu yd) and underdepth (1,212,000 cu yd) are approximately the same, leaving a net deviation from project depth of only 40,000 cu yd overdepth. In contrast, the prototype average overdepth (2,935,000 cu yd) is much greater than the average underdepth (989,000 cu yd), resulting in an average net overdepth of 1,946,000 cu yd, which is of the same order of magnitude as the average annual reported dredging

volume (2,098,000 cu yd). This shows that the model dredged volumes are a much more accurate measure of required model dredging volume than the reported prototype volumes are for the prototype dredging requirement.

Adjusted Dredged Volumes

127. The inaccuracy of prototype dredging volumes as a measure of the dredging requirement to maintain project depth is due to several variables in dredging operations. Variations in prototype dredged volumes can arise due to inaccuracies in location and dredging depth, dredge availabilty, maintenance funding levels, weather conditions, and other factors. Overdredging results in overdepth, water depths greater than project depth; while underdredging causes underdepth, depths less than project depth. Over long periods of time, overdredging and underdredging tend to average out in the absence of intentional advance maintenance, since overdredging one year can reduce required dredging in following years and underdredging will eventually have to be dredged to maintain project depths. However, to avoid contamination of short-term data by overdredging and underdredging, some means of adjusting the reported dredged volumes must be devised. There are several methods and rationales of adjustment, each having advantages and disadvantages. The methods presented herein offer special insights into the problem of comparing model and prototype dredging volumes.

For excess underdepth

128. The first method of adjustment simply includes the volume of material in the navigation channel that was underdepth this year in excess of the underdepth volume of the previous year's dredging. This excess from one year to the next is used rather than the total underdepth to avoid inflation of the dredging volume by underdepth that remains in the channel for several years and is not dredged. The adjustment is made

$$AD_u = RD + UD - UD' \qquad (10)$$

where

AD_u = dredged volume adjusted for excess underdepth

RD = reported dredging

UD = underdepth this year

UD' = underdepth of previous year

The result represents actual dredged volume plus material that should have been dredged but was not. The results of this adjustment to both model and prototype data are presented in Table 15.

129. After adjusting for excess underdepth, the previously observed discrepancy between overall model and prototype dredging volumes is greater. Adjusting by this method decreased the average model total dredging requirements to 888,000 cu yd and increased the prototype requirements to 2,244,000 cu yd annually.

130. The distribution of the adjusted volumes over the entrance channel sections for the model was 2 percent in the inner bar, 43 percent in the outer bar, and 55 percent in the approach channel. The prototype distribution was 28 percent in the inner bar, 17 percent in the outer bar, and 55 percent for the approach channel. The percentages were the same for the approach channel, but once again the inner bar channel of the model showed a lack of shoaling.

For excess underdepth
and excess overdepth

131. This method adjusts for excess underdepth and also for excess overdepth. If the channel condition at the end of the dredging operation has the same net volume deviation from project depth as for the end of the previous year's dredging, then the volume dredged this year would be the net amount of material that shoaled within the channel during the year. Adjustment to the dredging volume to reflect this is

$$AD_{uo} = RD + (UD-UD') - (OD-OD') \tag{11}$$

where

AD_{uo} = dredged volume adjusted for excess underdepth and overdepth

OD = overdepth this year

OD' = overdepth of previous year

The result indicates the volume that should have been dredged. The results of this adjustment to model and prototype data are also shown in Table 15. Negative numbers indicate a net scour, thus implying that no dredging would have been required. This is not strictly true, however, since the depth in some short segment of the channel could be small enough to require dredging to maintain project depth, even though the adjustment calculation for the entire channel section indicates a net scour.

132. The adjustment for excess underdepth and excess overdepth widens the gap between model and prototype dredging volumes even more. The model inner bar channel still shows a net scour and the overall average adjusted dredging volume in the model (496,000 cu yd) is still grossly low relative to the prototype average adjusted dredging volume (2,372,000 cu yd). Taking the years where the adjustment yielded a net scour in a section as no dredging (not a negative contribution), the model inner bar channel average dredging would be 0, the outer bar average dredging would have been 386,000 cu yd, and the approach channel results would not be affected. Then the average dredging requirement for the model would have still only been 819,000 cu yd. The prototype volumes would not change when ignoring net scour, since this was never the case. The large discrepancy between model and prototype overall dredging is still evident, and the relative agreement of individual channel sections is much the same as unadjusted volumes.

Dredging Requirements

133. The fact that the prototype average net deviation from project depth after dredging is overdepth of the same order of magnitude as the average annual dredging suggests that this large overdepth may be causing larger prototype dredging volumes than might be experienced if there were no overdepth. This is based on the assumption that a deep channel will exhibit greater shoaling on an annual basis than a shallower channel. To investigate this possibility the before-dredging prototype surveys were examined to determine the amount of dredging required.

134. The before-dredging prototype surveys were examined for areas in the navigation channel where the depth was 2 ft or more shallower than project depth, and the volume of dredging that would result if those areas were dredged to 2 ft deeper than project depth was calculated. For these areas of shallower depths, an average depth was determined and the increase in average depth required to attain project depth plus 2 ft was then multiplied by the shoaled area to obtain a dredging volume required. This calculation resulted in the volume of required dredging that would have resulted if the Galveston District guideline for determining when and where dredging is required had been followed. However, this volume does not include the material which deposited in the prototype channel during the dredging operation. This guideline was followed in performing model dredging. These calculations did not include any material above 2 ft below project depth if the depth were not shallower than 2 ft above project depth.

135. The prototype volumes determined by this method are presented in Table 16. Also shown in the table are the model reported dredged volumes. These results show that the prototype dredging required is indeed a very large volume, averaging 3,310,000 cu yd annually. The inner bar channel shows an average requirement of 446,000 cu yd, 14 percent of the average total requirement. The outer bar channel indicated an average requirement of 343,000 cu yd, 10 percent of total, and the approach channel averaged 2,521,000 cu yd required dredging, 76 percent of the average total annual requirement for the entrance channel. These prototype volumes are much greater than the model predicted volumes. For the entire channel the prototype volume, 3,310,000 cu yd, was 3.3 times the model's predicted volume, 997,000 cu yd. This determination of prototype dredging requirements shows that the large volumes of prototype dredging were not a direct result of large overdredging volumes.

Channel Conditions

136. The condition of the prototype navigation channel prior to initiation of realignment construction is shown in Plate 14. The

crosshatched area represents areas shallower than project depth. There was an area in the inner bar of the old channel (labeled "existing channel" in the plates) that was shallower than project depth covering about 20 percent of the inner bar channel. This shoal completely crossed the channel between ranges 45 and 46 close to the inner end of the channel. The maximum height of this shoal was about 2 ft above the old project depth. There was also a shoal crossing the prototype channel at the inner end of the approach channel, approximately between ranges 24 and 27. The maximum height of this shoal was about 4 ft above the old project depth. The remainder of the prototype channel was project depth or deeper. The model old navigation channel condition at the start of the plan 2 test (before construction) was project depth and the model bed outside the channel limits was molded to 1960 prototype conditions. The areas above project depth in the prototype channel were offset by areas below project depth, so that on the average the model and prototype channels were in approximately the same condition at the beginning of construction of the channel realignment.

137. Plates 15-38 present the conditions of the model and prototype navigation channels at the end of the construction of the channel realignment and each year for 6 years after completion of construction. Each plate showing the model condition of the channel at a particular point in the test is followed by the plate showing the prototype channel condition for the analogous point in time.

138. Table 17 lists the average depths for before and after dredging in the model and prototype for the inner bar, outer bar, and approach channels. The tabulated values are referred to in the following discussion of Plates 15-38.

139. The conditions of the navigation channel for model and prototype at the end of construction are shown in Plates 15 and 16. The model inner bar channel average depth was 42.0 ft (project depth). The prototype inner bar channel was 2 ft or more deeper than project depth over its entire length with an average depth of 44.8 ft. The outer bar channel average depths at the end of construction were 43.4 ft and 46.7 ft, respectively, for model and prototype. Both model and prototype

showed shallower depths on the south side of the outer bar channel. The average depths for model and prototype approach channels were 43.3 ft and 44.8 ft, respectively. Overall, the prototype channel at the end of construction was approximately 2 ft deeper than the model channel.

Inner bar channel

140. The inner bar channel of the model gradually deepened throughout the test with the small scour zone at the west end of the channel progressively scouring eastward. The average depth of the inner bar channel gradually deepened from 42.0 ft at the end of construction to 45.6 ft at the end of the model test, 6 years after the completion of construction. The inner bar channel of the model at the end of the test was 2 ft or more deeper than project depth over most of its length.

141. The prototype inner bar channel shoaled substantially during the first year after completion of construction, from an average depth of 44.8 to 41.1 ft. The shoaling was in the seaward two thirds of the inner bar channel with a scour zone at the inner end, just as in the model. The average depth in the prototype inner bar channel remained fairly stable during the 6 years of the study period, being maintained by large dredging volumes. In most of the before-dredging conditions, there was a long, narrow shoal on the south side of the seaward half of the channel section, and a similar shoal on the north side of the bayward end of the inner bar channel. The before-dredging conditions also showed that the scour zone in the inner end of the channel tended to remain along the south side in the inner third of the inner bar channel. The after-dredging conditions showed the maintenance dredging to be generally successful in removing the long, narrow shoals at the edges of the channel. Also, the scour zone after dredging generally extended farther seaward, over at least half the length of the channel. During the sixth year, however, there was a substantial loss of depth, and the shoals crossed the channel and elongated to partially fill the scour hole at the inner end of the channel.

Outer bar channel

142. The outer bar channel in the model test had a shoal along the entire length of the south side of the channel. A zone of

deeper-than-project depths appeared in the middle of the channel section after 2 years and gradually grew and elongated. By the end of the sixth year, the zone had migrated partially into the inner bar channel. The model outer bar channel was fairly stable with the average depth varying little from 43.4 ft at the end of construction to 43.8 ft at the end of 6 years before dredging.

143. During the study period, the prototype outer bar channel gradually deteriorated from virtually all depths greater than 2 ft deeper than project depth (average depth of 46.7 ft) at the end of construction to a channel with a large shoal tapering from the inner bend of the channel between the inner and outer bar channels, with deeper depths remaining on the northern side of the channel. At the end of the first year, before dredging, the average depth in the prototype outer bar channel was 44.7 ft. The average depth for before-dredging conditions stayed approximately the same for the remainder of the study period. The prototype outer bar channel showed a tendency toward deeper depths on the north side at the inner channel bend, then crossed the channel to deeper depths on the south side of the channel at the outer channel bend, the junction with the approach channel.

Approach channel

144. The model approach channel consistently shoaled in its inner end just seaward of the junction with the outer bar channel. This shoal was removed by the first year's dredging, but returned during the second year. The dredging after the second year did not remove the shoal, and it continued to expand through the fifth year, when the dredging of that year partially removed it. It promptly shoaled again during the sixth year.

145. Another area of the model approach channel shoaled completely across the channel, in approximately the middle of the approach channel, range 16 of the model grid system. The dredging during the first two model years essentially removed the shoal, but it was not completely removed for the remainder of the model test and obstructed the entrance channel.

146. A small zone of scour at the seaward end of the model

approach channel expanded gradually throughout the six test years but never became very large.

147. The prototype approach channel had a scour zone rather than a shoal at the west end of the section. By the sixth year, however, this scour zone had essentially disappeared. Shoaling occurred over the entire outer 75 percent of the length of the channel. The dredging operations of the first year diminished the shoal somewhat, but the second year it returned. The second year's dredging operation almost completely removed the shoal. The shoaling of the third year was confined toward the inner half of the approach channel while depths within 2 ft of project depth remained in the outer end. The dredging of the third year removed part of the shoal, leaving a long, narrow shoal on the north side of the channel. The fourth year the shoal expanded again to cover most of the outer approach channel and was then partially dredged that year. The fifth year there was not a great deal of change to the shoal in the outer approach channel, but the scour zone at the inner end had filled considerably. During dredging operations of the fifth year, the scour hole deepened and expanded to its previous size while the shoal in the outer end of the channel grew to what would normally appear a before-dredging condition. Consequently, the sixth year shoaling once again filled most of the scour zone, and the shoal completely covered the outer 75 percent of the approach channel.

148. Discrepancies between the model and prototype channel conditions are not striking. In the junction between the outer bar and approach channels, the model had a shoal and the prototype had a scour zone. The model showed a scour zone in the outer end of the approach channel, not present in the prototype; and the prototype generally exhibited considerably more shoaling throughout the approach channel. In the prototype, the shoal area on the north side of the inner bar and the scour area on the north side of the outer bar were considerably larger than in the model. At other than these locations, the patterns of scour and fill were similar.

Channel Scour and Fill

149. Based on the hydrographic soundings, scour and fill in the navigation channel for model and prototype were determined and contoured (Plates 39-60). These contoured zones of scour and fill show the areas where the greatest changes in depth occurred. The scour-and-fill areas for model and prototype are presented for the periods between dredging operations and for the periods during dredging.

150. The average depth changes for the three channel sections in model and prototype are presented in Table 18. Negative depth changes are increased depth, or scour, while positive depth changes are reduced depth, or fill. The data show that the depth changes in the prototype are larger than those in the model. Also, the model inner bar general scour is demonstrated by increasing average depths.

Between dredgings

151. The scour and fill that occurred in model and prototype navigation channels each year between dredging operations for the first 6 years following channel realignment are shown in Plates 39-50. These scour-and-fill maps represent depth changes which occurred between one year's after-dredging condition survey and the next year's before-dredging condition survey. The model plate precedes the corresponding prototype plate for each year. The zones of scour and fill are broken at 3-ft increments; zones where neither scour nor fill exceeded 3 ft essentially are designated as no change.

152. In the first year, the model shoaling was concentrated mainly at the junction of the outer bar and approach channels while the prototype shoaling was mainly in the inner bar channel and the approach channel, covering much larger areas. During the second year, the model again shoaled at the outer channel bend as did the prototype.

153. The model continued to shoal at the junction of the outer bar and approach channels for each year of the 6 years of the test. There were some small zones where the scour exceeded 3 ft in the west end of the inner bar channel and the east end of the outer bar channel during the third and sixth years of the model test. All of the zones

of scour or fill greater than 3 ft of change were over small areas in the model. Similarly, the prototype changes each year were primarily fill with infrequent scattered small zones of scour.

154. The prototype experienced widespread shoaling during the first, third, and sixth years of the postconstruction period. During the fourth and fifth years of the period, the prototype zones of both scour and fill in excess of 3 ft were small and scattered over the entire entrance channel.

155. The model changes in depth between dredging operations were generally not as great or as widespread as the prototype changes. The model changes in excess of 3 ft were primarily in the outer bar channel, while the prototype changes were over much larger areas and occurred in all sections of the entrance channel.

During dredging

156. The zones of scour and fill in excess of 3 ft occurring during the dredging operations in model and prototype are shown in Plates 51-60; the model plate precedes the corresponding prototype plate.

157. The model experienced only scour during the dredging operations, as would be expected with model operation stopped during removal of shoaling material. The model zones of scour in excess of 3 ft were at the junction of the outer bar and approach channels for every year of the test and nowhere else in the model channel. This was the case because the model dredging operations were only in the areas where dredging was required, and the junction referred to above was the only area of the model channel that showed substantial shoaling during the model test (between dredgings).

158. The prototype changes in depth during the dredging operations were much more widespread than in the model, just as the changes between dredgings were more widespread. The amounts of scour during the first, second, and fifth dredging years of the period were substantially greater than during the third and fourth years of dredging operations. Shoaling occurred in some areas during the prototype dredging period, but they were not very large except in the approach channel for the third year of dredging.

159. In general, the large prototype dredging volumes resulted in scour in excess of 3 ft over a much broader area of the entrance channel than the scour resulting from the small amount of model dredging.

Bed Conditions

160. A problem encountered at the time of model verification was the limited number of prototype hydrographic soundings covering a sufficient area of the movable bed. Very few maps were available that covered a wide enough area from which scour-and-fill maps could be developed for use in verification of the movable bed. As discussed in paragraph 86, the surveys of 1950 (Plate 10) and 1960 (Plate 11) were used to develop the scour-and-fill map (Plate 12) for model verification. After the initiation of the model study, a prototype survey was made in 1962 covering a large area of the movable bed, shown in Plate 61. The 1960 and 1962 conditions of the bed are quite similar.

Before construction

161. The condition of the model and prototype beds prior to initiation of channel realignment are shown in Plates 62 and 63. The model was molded approximately to the 1960 prototype bed condition, the data used for initiation of all model tests. The actual model condition as molded was sounded prior to each test. The prototype condition in Plate 63 was the 1964 bed condition just prior to initiation of construction and was similar to the 1962 bed condition.

162. The general similarity of the bed conditions in model and prototype is evident. Both had large zones of shallow depths inside the landward ends of both jetties. The contours in the shallow zone next to the inner end of the north jetty roughly parallel the original channel, tapering into the north jetty. The large spit next to the inner end of the south jetty is similar in both model and prototype, having the same basic shape and location.

163. Just seaward of the outer ends of the jetties, the depths were in excess of 36 ft in both model and prototype. At the tip of the north jetty, the prototype scour hole was in excess of 42 ft below mlw,

whereas the model was slightly shallower. In both model and prototype, the 36-ft contour crossed just offshore of the tip of the north jetty and approached the navigation channel before turning into the inlet and tapering toward the north jetty. The prototype depths between the 36-ft contour and the north jetty were much shallower than those in the model. The prototype 36-ft contour enclosed a 24- and a 30-ft contour.

164. Relatively deep depths were just seaward of the outer end of the south jetty in both model and prototype. However, the 36-ft contour trailed into the inlet in the model, while in the prototype it ran seaward somewhat before turning into the inlet near the navigation channel.

165. There was a zone of relatively deep depths along the middle of the north jetty in both model and prototype, where the original navigation channel came closest to the jetty. These depths threatened to undermine the north jetty in the prototype, as described previously. The prototype depths along the jetty slightly exceeded 36 ft, while the model was about 4 to 6 ft shallower in that area. A zone of water deeper than 36 ft extended throughout the original navigation channel in both model and prototype. Throughout approximately the seaward 3 miles inside the jetties, the widths between 36-ft contours averaged about 2100 and 1650 ft in model and prototype, respectively.

166. Between the inner bar channel and the large spit adjacent to the south jetty, the model depths were slightly deeper (2 to 8 ft) than the prototype depths.

167. There is evidence of a submerged ebb flow spit trailing seaward from the spit next to the south jetty in both model and prototype. This submerged spit was approximately parallel to the alignment of the proposed channel, The spit is noticeable in the model 24- and 30-ft contours, while it is very much evident in the prototype 6-, 12-, 18-, 24-, and 30-ft contours. Between the ebb flow spit and the south jetty, a secondary channel was present in both model and prototype, apparently predominantly for flood currents.

168. At the inner end of the jetties, just north of the large spit at the inner end of the south jetty, another secondary channel

existed in both model and prototype. In the model, the portion of this channel deeper than 36 ft covered a larger area than the analogous prototype zone.

169. There were some discrepancies between the details of the conditions in model and prototype prior to construction, but the general conditions were the same. The zones of deep and shallow depths were located approximately the same and were of the same general dimensions. The agreement is considered to be good.

After construction

170. The conditions of the model and prototype beds for several years after the completion of construction of the realigned navigation channel are presented in Plates 64-69. Plates 64 and 65 show the conditions of model and prototype 2 years after construction was completed. The model and prototype conditions 5 years after the completion of construction are shown in Plates 66 and 67, respectively. Plate 68 shows the model bed condition 6 years after construction and Plate 69 shows the prototype bed 6-1/2 years after channel realignment.

171. During the period of this study, the prototype spit inside the south jetty changed substantially while the model spit at that location experienced only minor change. Comparison of Plates 63 and 69 shows that the prototype spit grew considerably along the length of the south jetty (both seaward and bayward) and changed shape.

172. The model spit inside the south jetty, in contrast, maintained approximately the same shape throughout the test but enlarged slightly in size. Comparison of Plates 62 and 68 shows that the model spit maintained the same general shape but widened into the inlet, with the position of the maximum width of the spit, to the -6 ft contour, remaining in the same location. The main body of the model spit did not expand seaward, but material deposited adjacent to the south jetty, lengthening the thin seaward extension of the spit inside the jetty.

173. At the end of 2 years after the completion of the realignment, the deepwater zones at the inner end of the navigation channel were on somewhat different alignments in model and prototype. Based on the -30 ft contour south of the new navigation channel and the

-36 ft contour north of the previous navigation channel, it can be seen that the model deepwater zone was almost exactly aligned with the inner bar portion of the new navigation channel. The prototype deepwater zone alignment was rotated slightly counterclockwise with respect to the navigation channel. In subsequent years, the prototype zone of deep water tended to lie on a better alignment with the navigation channel, as was the case in the model. However, due to prototype maintenance of the anchorage basin north of the realigned channel, the prototype had a much greater width between the -36 ft contours around the navigation channel, as is particularly evident in Plates 67 and 69.

174. The ebb flow spit trailing from the spit adjacent to the south jetty (as shown by the -18 ft contour) was much better defined in the model 2 years after construction (Plate 64) than before construction (Plate 62). Thus this feature became progressively less pronounced in the model (Plates 66 and 68) as the -18 ft contour rotated clockwise. By moving closer to the south jetty, the spit encroached on the secondary channel, which had narrowed considerably by the end of the test.

175. The prototype submerged ebb flow spit remained in the same location and alignment, parallel to the inner bar channel. The submerged spit is evident in the -12, -18, -24, and -30 ft contours at 2 and 5 years after construction (Plates 65 and 67), but only in the -18, -24, and -30 ft contours at 6-1/2 years after construction (Plate 69). The prototype secondary channel between the spit and the south jetty was present throughout the course of the study period.

176. The slope of the model bed from the northernmost tip of the shoal adjacent to the south jetty down into the deepwater zone in the inner bar channel (at about range 37 or 38) was much steeper than the corresponding slope in the prototype. This steep model slope was apparently caused by the expansion of the shoal toward the deepwater zone in conjunction with the shifting of the deepwater zone to the south.

177. The old channel in the model tended to stay deep, while the prototype old channel shoaled fairly rapidly. Plate 68 shows that after 6 years the model still had a zone in the old channel at about range 40 with depths in excess of 42 ft. After 6-1/2 years, the prototype old

channel was obscured by the maintenance of the anchorage basin and shoaling in the old channel (Plate 69).

178. The model scour hole near the end of the south jetty (Plates 64, 66, and 68) tended to be slightly inside the end of the jetty, whereas the prototype scour hole was slightly outside the end of the jetty (plates 65 and 67).

179. At the beginning of the study period, prior to construction, the prototype -36 ft contour between the navigation channel and the tip of the south jetty was convex seaward. In the model, the -36 ft contour in that area was concave seaward before construction and remained so throughout the test. During the period of the study, the prototype contour retreated landward and also became concave seaward, as in the model. The area appears to have scoured to reflect the presence of the secondary channel adjacent to the south jetty.

Bed Scour and Fill

180. The hydrographic changes occurring in the model from the beginning of the channel realignment test to 2 years after the completion of construction, a 4-year period, are shown in Plate 70. The corresponding prototype changes from initiation of construction to 2 years after its completion, a 4-1/2-year period, are shown in Plate 71.

181. Generally, the agreement between the model and prototype zones of scour and fill is good. Both model and prototype had scour zones along the new inner bar channel, as was observed during the verification periods in that area. In the model, the zone of heaviest scour was immediately adjacent to the navigation channel, while the prototype zone of heaviest scour was roughly midway between the navigation channel and the south jetty.

182. There were two zones of fill in both model and prototype along the south jetty. These model shoals were much heavier than the prototype shoals. As in the verification test, the model shoals in this area were several hundred feet (prototype) north of the south jetty, while the prototype shoals were immediately adjacent to the jetty. The

prototype showed a shoal just south of the outer bar channel in an area where the model showed scour.

183. The prototype showed a large zone of scour between the original and realigned channels. This scour is primarily due to the construction and maintenance of the anchorage basin in that area. The model showed shoaling in that area, not having had any anchorage basin included in the construction sequence test.

184. There was a zone of heavy scour just south of the outer bar channel in both model and prototype. The prototype zone was more toward the outer end, while the model zone was more toward the inner end of the outer bar channel.

185. Between the old channel and the north jetty there was generally shoaling in both model and prototype. The prototype shoaling was very heavy in the old channel itself and virtually everywhere along the north jetty. The model shoaled over most of the old channel and along the north jetty, but the model also had a zone of scour between the old channel and the north jetty at the main bend in the old channel (ranges 38-42). The extensive prototype shoaling over this area probably was accelerated by the maintenance of the anchorage basin. The area used for disposal of dredged material during construction of the new channel showed heavy shoaling in both model and prototype.

186. The agreement between the model and prototype hydrographic changes from the beginning of construction to 2 years after its completion is generally good. The model shoaling tended to be fairly well balanced over the areas where it did shoal, while the prototype shoaling along the north jetty was much heavier than the shoaling south of the navigation channel.

187. The changes that occurred in the model and prototype bed from 2 to 6 years after the completion of channel realignment are presented in Plates 72 and 73, respectively. The agreement during these 4 years is not as good as during the first half of the study period.

188. North of the new channel, the model had a large shoal adjacent to the middle of the north jetty and in the old channel where it ran closest to the north jetty. About 5000 ft seaward of this

location (in the disposal area) there was a region of minor to moderate scour. This could indicate a net upstream movement of material from the disposal area, although there was also an area of substantial shoaling seaward of the disposal area at the outer end of the north jetty. Landward from that area the model had minor scour in the old channel with shoaling both north and south of the old channel. At the extreme inner end of the old channel, just north of the junction of the old and new channels, there was another large shoal in the model.

189. The prototype generally scoured north of the realigned channel. North of the old channel where it ran closest to the north jetty the prototype had a very heavy amount of fill, in the same area where the model had heavy fill. This also indicates a possible net upstream movement of sediment from the disposal area. In the old channel at the innermost two bends, the prototype shoaled over a fairly large area that extended to the north jetty. Between the old and new inner bar channels the prototype experienced minor scour. Throughout the outer 2 miles of the jettied entrance, the prototype experienced heavy scour, both north and south of the realigned channel.

190. Both model and prototype had zones of scour around the new inner bar channel alignment. The model zone of heaviest scour was again along the alignment of the channel, while the prototype heaviest scour was about 1000 ft south of the channel.

191. Between the realigned channel and the south jetty the prototype underwent general scour with several small shoal areas. The model in that area experienced two fairly large zones of fill in addition to extensive areas of scour. The largest model shoal extended from about the outer 3000 ft of the south jetty across the entrance to the outer end of the north jetty. The model also had a heavy fill area adjacent to the spit at the inner end of the south jetty, probably fed from the spit by ebb currents.

192. The greatest difference in the changes observed in the model and prototype during the last 4 years of the study period was at the outer end of the jettied entrance. The prototype scoured over almost the entire cross section while the model shoaled across the ends of the

jetties. With the exception of the ends of the jetties, the agreement was fair.

Storm Effects

193. Due to the large hydrographic changes that can occur during a hurricane or tropical storm (paragraph 54, Plate 6), it is of interest to consider the effect a storm may have in the determination of prototype long-term scour and fill. Additional prototype scour-and-fill maps were generated to illustrate the difficulty of determining the long-range trends of the inlet. Plate 74 shows the scour and fill that occurred between 1960 and 1962, the 2 years after the period used for model verification. Plate 6, discussed previously, shows the hydrographic changes that occurred during the passage of Hurricane Carla in September 1961 (Hurricane track No. 41 in Plate 4). The changes shown in Plate 6 were determined from the closest surveys before and after the passage of the storm (14 June 1961 and 28 October 1961).

194. The correlation between the changes occurring during the passage of Hurricane Carla and the changes over the longer period of 1960 to 1962 is evident. The scour zones at the base of the south jetty, just inland from the spit, are in the same general location and of the same magnitude. Both maps show a general scour through the center of the inlet and show shoaling at the inner end of the north jetty just north of the old navigation channel; there is also shoaling along the outer end of the north jetty (although much more pronounced in Plate 6) with a scour zone at the very tip of the jetty. Two main shoaling areas exist between the proposed realigned navigation channel location and the south jetty--one is just north of the spit at the inner end of the south jetty and the other is just inside the outer end of the south jetty. Comparison of Plates 6 and 74 shows that the passage of a hurricane or tropical storm in the Gulf of Mexico may cause persistent changes in the bed of Galveston Harbor entrance.

195. In order to illustrate the sensitivity of the prototype scour-and-fill patterns to the surveys chosen for workup, a

scour-and-fill map was made for the period 1950 to 1962 (Plate 75). This map can be compared with the 1950 to 1960 scour-and-fill map (Plate 12), used for original model verification, and the 1960 to 1962 map (Plate 74). No change in the general location of the zones of scour and fill is observed in the 1950-1962 map as compared with the 1950 to 1960 scour-and-fill map. There is, of course, some change in the specific locations and sizes of the scour-and-fill zones. The 1950 to 1962 map shows scour at the outer end of the south jetty, while the verification map shows fill. There is an area of fill at the outer end of the north jetty in both maps, but the area is greatly reduced and the shoaling zone is surrounded by a larger zone of scour in the 1950 to 1962 map. The general area outside the jetties for the 1950 to 1962 map indicates general scour with some shoaling north of the navigation channel far offshore, whereas the verification prototype scour-and-fill map indicates general fill offshore.

196. Just north of the innermost channel bend in the original navigation channel, the 1950 to 1962 scour-and-fill map indicated a zone of heavy fill. In the 1950 to 1960 map, the zone of heaviest shoaling in that area was just south of the channel near the bend. The zone of severe scour between the old navigation channel and the south jetty extends farther upstream in the 1950 to 1962 map than in the 1950 to 1960 map. Also, in the area where the navigation channel passed closest to the north jetty, the scour zone just south of the channel is larger in the 1950 to 1962 map.

197. The scour-and-fill maps of 1950 to 1960 and 1950 to 1962 show the same general characteristics of scour and fill in most areas of the bed, but the scour zone in the area of the relocated inner bar channel of the 1950 to 1962 map shows better agreement with the model verification (Plate 13) than does the 1950 to 1960 map. The 1960 to 1962 map (Plate 74) demonstrates some of the same general scour-and-fill patterns exhibited by the 1950 to 1960 and 1950 to 1962 maps, but in the area between the realigned navigation channel and the south jetty there was considerably less scour and considerably more shoaling in 1960 to 1962.

198. The effects of storms can also be evident in prototype dredging volumes. During the period between 1950 and 1955, three storms (storms 3, 5, and 15 in Plate 3) passed close enough to Galveston to have generated waves with sufficient energy to alter the bathymetry at the inlet. Two of these storms were prior to FY 1950 dredging which was the largest dredging volume of the 1950's, with 2,222,000 cu yd that year (Table 4). The other storm passed in July 1954, but the dredging for FY 1955 was about average with 1,106,000 cu yd of dredging. During the period 1956 to 1961, a large number of storms passed the Galveston area. The storms passing closest to the inlet were Audrey and Bertha in 1957, Debra in 1959, and Carla in 1961 (storms 27, 28, 35, and 41, respectively, in Plate 4). Audrey and Bertha passed very close to the Galveston area but in a direction that would have produced strong offshore winds as the storm approached land, which could have caused large ebb velocities through the inlet, causing scour. The subsequent FY 1958 dredging volume was very low, 515,000 cu yd, reflecting this possibility. In 1959, Hurricane Debra passed directly over the Galveston area, and the FY 1960 dredging volume was 1,677,000 cu yd. Hurricane Carla passed in 1961, and the dredging volume for FY 1962 was 2,148,000 cu yd. Dredging after Hurricanes Debra and Carla was considerably more than the preenlargement average of 1,240,000 cu yd. In 1958, Hurricane Ella (storm 32 in Plate 4) passed by somewhat farther from Galveston Bay and apparently did not significantly influence the dredging rate (1,053,000 cu yd).

199. During the postconstruction period, 1967 to 1974, two tropical storms and two hurricanes passed the area (storms 65, 66, 67, and 70 in Plate 5). In 1970, tropical storm Felice passed very close to the area but the FY 1971 dredging was normal for the postconstruction period, 1,910,000 cu yd. In 1971, two hurricanes, Fern and Edith, passed the area, and the FY 1972 dredging volume was a record 3,150,000 cu yd. In 1973, tropical storm Delia came ashore just west of Galveston, but there was no accurate dredging volume reported for the year due to the sinking of the dredge *MacKenzie*. However, the channel condition prior to the dredging operation (Plate 38) showed that the channel required a great deal of dredging. In 1970, Hurricane Celia (storm 63 in Plate 5) passed

somewhat farther from the inlet area without any adverse effects on the dredging requirements for FY 1971 (1,910,000 cu yd).

200. The model study included a test that simulated a storm by placing 3,000,000 cu yd of material inside the base of the south jetty. This was one possible result of a storm; however, the effects of a storm could vary to also have a large volume of material deposited inside the north jetty, or perhaps at the tips of the jetties. Results from the model storm simulation did not show a large effect on average channel shoaling volumes.

201. The passage of hurricanes and tropical storms has a significant effect on the changes in the general prototype bed and on the dredging requirements. Each storm that passes has a different effect on the area. Some will cause shoaling while others may cause scour in the inlet. This makes model verification and postconstruction verification difficult, because the precise effects of the storms were not present in the model testing.

202. The number and frequency of tropical storms in the Gulf of Mexico and in the northwest corner of the gulf have been summarized in Table 19 for the periods of interest. The periods used for bed scour and fill for original and postconstruction verification had the same average number of hurricanes in the entire gulf each year (1.7), but the original verification period averaged approximately one more tropical storm each year than during the postconstruction period (1.9 and 0.8, respectively). The average number of hurricanes in the northwest corner of the gulf each year was approximately the same (0.5 for the original verification period and 0.6 for the postconstruction period). Tropical storms were twice as frequent in the northwest corner of the gulf in the preconstruction period over the postconstruction period (0.6 and 0.3 storms each year, respectively).

203. The period of data used for original verification of channel dredging requirements (1957-1961) averaged 1.4 hurricanes and 2.0 tropical storms each year in the entire Gulf of Mexico. That was considerably different than the postconstruction period of dredging data (1968-1973) frequency of 1.7 hurricanes and 0.8 tropical storms each year. In

the northwest corner of the gulf, the frequency of hurricanes was similar (0.6 and 0.5 for pre- and postconstruction periods) and the frequency of tropical storms was once again twice as great in the preconstruction period (1.0 and 0.5, respectively).

PART V: DISCUSSION

204. Postconstruction verification of a movable-bed coastal model is a perplexing undertaking and the Galveston Harbor entrance model is not an exception. If the complexity of the phenomena involved makes modeling difficult, then evaluating how well the phenomena are modeled becomes an almost insurmountable task. The foremost problem lies in determining the effects of substituting a simplified set of model boundary conditions for the complex, changing, and poorly defined boundary conditions of the prototype. In addition, the boundary conditions of the prototype may have been significantly different between the preconstruction and postconstruction periods. Since the bed condition changes for one hurricane (Carla) were almost as great as those for the verification period, the problem of nonmatching boundary conditions is obviously formidable.

205. Under circumstances such as these, where boundary conditions strongly affect the analysis, the best approach is to use a period of prototype data that is long enough to average out short-term discrepancies and detailed enough to exclude singular events such as Hurricane Carla. For Galveston Harbor entrance, both preconstruction and postconstruction prototype data periods were long enough to average tidal conditions, most aspects of wave climate, and typical local storms (northers), but not long enough to provide for an "average" hurricane effect.

206. To complicate matters more, differences between the plan tested in the model and the plan constructed in the prototype must be contended with. The prototype construction included the anchorage basin which was not included in the model construction precedure test, and the size of the dredged material disposal area adjacent to the north jetty was different in the model and prototype.

207. In the discussion of the Galveston Harbor entrance model study presented here, attention will first be given to the modeling techniques used relative to the basic modeling criteria for sediment transport and to the prototype boundary conditions as can best be

defined. Then the results of the comparison between the model predictions and the postconstruction prototype observations will be discussed in light of the modeling techniques employed.

Modeling Techniques

208. At the initiation of the model study, the first problem encountered was a lack of adequate prototype data. As described previously, there was a lack of prototype hydrographic surveys covering a sufficient area of the movable bed of the model to give an indication of an average bed change without fear of contamination by short-term fluctuations in the bed due to storms. The littoral environment was not well understood at that time and wave statistics for the area were limited.

209. There is some question about the quality of the maintenance dredging data. At the time of the study, dredging volumes for the period 1953 to 1961 were supplied by the Galveston District. Those data are compared with the volumes reported by OCE (1953-1961)[9] in Table 20. Hopper dredge report sheets (Form No. 27) obtained from the Galveston District for FY 1959 through FY 1974 were used to determine maintenance dredging volumes for fiscal years 1959 to 1961 and calendar years 1958 to 1961 and these are also shown in Table 20. Table 20 shows discrepancies between the OCE Annual Report data, the volumes determined from the hopper dredge sheets, and the data supplied by the Galveston District. The average annual dredging for each of the sources of data is not greatly different (roughly ±10 percent from the District's figures) and the data used for verification yield a representative volume; but little confidence can be placed in a specific prototype volume of dredging quoted for a particular year.

Geometric similitude

210. The first step toward obtaining proper modeling of sedimentation is geometric similitude. This is generally ensured by the proper reproduction of the morphology around the inlet, the jetties, and the offshore contours. The accuracy of molding the movable bed of

the model was sufficient to obtain geometric similitude with the prototype. The differences in the plans tested in the model and constructed in the prototype were not large enough to destroy the general similitude, but they may have caused local differences in the results.

Hydraulic similitude

211. The next concern in obtaining proper sedimentation modeling is tidal hydraulics. As discussed in paragraphs 79 and 95, during sedimentation verification current velocities were increased 35 percent to obtain adequate bed movement. This is not surprising when the verification of the current velocities is examined. Plate 9 shows the quality of the reproduction obtained at four velocity stations (middepth), A-1, B-2, C-2, and F-3; locations of these stations are shown in Figure 1. Sta A-1, located in the Galveston Channel, shows the best agreement as would be expected since it is located in a narrow channel where little concern must be given to the transverse velocity distribution. Sta B-2 and C-2 are located well into the inlet, almost in the bay. This area is of importance with regard to sediment transport, being the area from which bay material would be fed into the inlet on ebb currents. Both stations show the velocities to be generally low in the model. Sta F-3 is between the outer ends of the jetties in the navigation channel in an area of large bed movement; at that station, the model velocities are also low.

212. Table 8 shows the relations between the model and prototype current velocities at sta B-2, C-2, and F-3. At all three stations the average flood and ebb velocities and maximum flood and ebb velocities are lower in model than in prototype. The average ratio of average and maximum velocities from all three stations is 1.3 (prototype to scaled model). Therefore, the 35 percent increase in model velocities resulted in improved hydraulic agreement rather than a distortion of hydraulic similitude.

213. An important part of the general hydraulic similitude of a tidal inlet model is flow reversal. This phenomenon can have an important impact on the general sedimentation characteristics of the inlet since it causes sediment moving through the inlet to be retained much

longer than would occur under steady-flow conditions. For the operation of the model during the sedimentation verification, the procedure developed involved only 12 reversals of flow for each model year. The prolonged periods of maximum flows in the model could have allowed a greater development of current channelization than could occur in the prototype. It is not reasonable to expect as many reversals per year in the model as in the prototype, but the absence of them due to prolonging the maximum flows may have had a profound effect on the modeling of the sediment transport, particularly in the inner bar channel where tidal currents are of greater importance than waves in the transport of sediment.

214. Because of difficulties (cost and more complex operating techniques) associated with the use of salt water in the model, it was operated with all fresh water. This was believed justified due to the low freshwater discharge in the prototype except for extremely short periods of high flow from the Trinity River when the inlet area becomes partly mixed. This was a step away from hydraulic similitude with the prototype.

215. During high freshwater inflow periods in the prototype, the vertical salinity gradient experienced in the inlet area is great enough to set up a net transport bayward at the bottom in some areas of the inlet. With high inflow there will also be an increase in the supply of fine bay sediments to the inlet area. The partly stratified condition in the inlet can create a trap for this material, somewhere in the inner portion of the inlet. This process may have been a contribution to the finer materials found in the prototype inner bar. This phenomenon would not have been successfully modeled because the model sediment did not have a large fraction of finer materials. Even if the model were operated with salt water in the Gulf of Mexico, great difficulties would have been encountered in simultaneously modeling the material transport at the outer portions of the bed and the sedimentation characteristics of the bay material.

216. A firm conclusion about the effect on model results of not reproducing salinity gradients and a full sediment supply from the bay

cannot be drawn from the available data. The prototype bed samples suggest such an effect would occur, but it is believed that the magnitude of error introduced would be relatively small.

217. In the outer portions of the inlet, wave reproduction is of greater importance to the sediment transport. The single wave used in the model, with a prototype height of 5.0 ft, a prototype period of 7.7 sec, and from a direction S37°E, appears to have been a good choice for a single representative wave but does not represent the variation in the prototype waves that produces a varying littoral environment with large changes in the direction and magnitude of transport along the coast. As discussed in paragraph 49, the gross transport is three to six times the net transport in the area of Galveston. The single wave direction used in the model did not adequately reproduce this large variation in the littoral transport; however, attempts to improve the verification using two wave directions were unsuccessful.

218. The wave height and period used in the model study appear to be representative of wave climate that contributes most to sediment transport. As shown in Table 2, 56 percent of the time the wave height was less than the model wave height of 5.0 ft. The model period of 7.7 sec was greater than about 85 percent of the wave periods observed. There were not sufficient prototype wave data to determine a reliable significant wave height, nor is there an adequate definition of an average wave height for sediment transport; but the height and period used in the model appear to have been reasonable in the absence of better information.

219. As described in paragraph 98, the model wave diffracted as if it were a much longer wave. The error would be noticeable only in the area of the inner bar channel for the wave direction used in the model.

220. The model wave was generated only while the tide generator was being operated; the waves were not generated during the prolonged periods of maximum flows. This means that the model waves were being generated only about 30 percent of the model operating time and that was during the periods of lower current velocities. Attempts to improve

the verification by extending the duration of wave generation were unsuccessful.

Sediment transport

221. Scaling of the model sediment grain size was governed largely by practical model operation considerations. Once crushed coal was chosen, grain size alone could be varied. An absolute minimum size would have been that below which the particles floated due to surface tension, since a firm bed could not be maintained under those conditions. The actual criterion used for grain size, that being the size at which ripples did not form on the bed, simplified sounding of the bed; but it did not result in a favorable value of Δ_{F_*} . The resulting product of sediment size and submerged specific gravity was not an optimum choice for sediment motion. As described in paragraph 101, the lack of F_* similarity was more severe in those areas not exposed to vigorous wave action.

222. The scale effects caused by inaccurate modeling of the particle Reynolds number are not considered to have been great (see paragraph 102).

223. It is doubtful that sediment supply to the model inlet was large enough. The representative wave direction discussed earlier probably would not supply a sufficient quantity of littoral material from the updrift and downdrift beaches. Supply from the bay may or may not have been adequate, although it seems likely that a supply equal to the volume of finer grained sediments found in the inner bar area was not produced by the model.

224. If it is accepted that a low value of Δ_{F_*} resulted in a reduced capability to transport sediment, then the orientation of the verification wave can be understood. Since the size of tidal inlets can be explained as a balance between the sediment transporting power of the tidal currents and the sediment supplied by littoral transport, it can be seen that a reduced transport power in the model inlet had to be matched by a reduced sediment supply to retain the inlet's characteristic cross-sectional area and obtain proper shoaling volumes. The reduction in sediment supply due to a wave almost parallel to the

shoreline was thus a necessary adjustment to obtain shoaling verification.

225. No attempt was made to simulate windblown sediment supply from adjacent beaches. The relative volume of windblown deposits in the prototype is probably small, but the lack of such a supply may have been the reason that no substantial change occurred in the spit at the inner end of the south jetty.

226. Prolongation of model maximum tidal flows with relatively fewer flow reversals may have affected sediment transport patterns and thus deposition in the model inlet, and may have also caused relatively greater flow channelization.

227. Another factor affecting sediment motion is the bed material's angle of repose. Since both model and prototype have repose angles of about 30° in air, model distortion results in the coal holding too mild a slope. This affects incipient motion, but as discussed previously, incipient transport is of lesser importance in the inlet. A greater effect will be the response of the bed to creation of artificially steep slopes by dredging. In the absence of agitation, the model sediment would have sloughed into newly dredged channels more rapidly than that of the prototype.

Dredging similitude

228. The dredging techniques and their effects were different in model and prototype. The prototype dredge scheduling, inaccuracies in locating the dredge, dredge operator differences, and weather conditions tend to make the reported dredge volumes an unreliable indication of the dredging required for a specific year. In contrast, in the laboratory environment of the model, areas where dredging is required and the volume required are most easily determined. The depth of the dredge cut is more accurately regulated and the volume of dredging is more accurately measured. Because of these differences, the method of adjusting the dredged volumes becomes very important.

229. The reported prototype dredge volumes were less than the net hydrographic change (scour) during the dredging operations as determined by analysis of the before and after surveys. This indicates that during the dredging operation there was some effective agitation

dredging in the inlet. The ratios between the net hydrographic volume changes during the dredging operations and the reported prototype dredging volumes averaged 1.57 for the inner bar channel, 1.17 for the outer bar channel, and 1.36 for the approach channel. The higher values for the inner bar and approach channels perhaps reflect the scouring of finer material from the inner bar channel and the greater movement of material in the approach channel by wave action.

230. The model, on the other hand, showed that the net hydrographic change during the model dredging operation was less than the volume of material removed from the model. There was no model dredging performed in the inner bar channel; therefore, no ratio can be computed there. However, in the model outer bar and approach channels the ratios between net hydrographic volume changes during dredging operations and the reported dredged volumes were 0.41 and 0.38, respectively. Agitation dredging as in the prototype was not possible because the model was not in operation during dredging. Rather, the model method of dredging, using the wide dustpan, may have caused eddies around the edges of the dustpan that brought material into the channel. This, plus more rapid sloughing into the channel due to the distortion of the model, could have been the cause of the difference between the volume removed from the model channel and the net volume change.

231. From the above discussion and examination of the before-and-after channel condition maps (Plates 15-38) it is obvious that both model and prototype dredging methods were imprecise. Their imprecision is of a nature that makes meaningful comparison between model and prototype volumes difficult. A further complication is introduced by the fact that during construction the prototype channel was dredged an average of more than 2 ft deeper than the model depths. The possibility cannot be ignored that this overdredging could affect shoaling characteristics of the inlet for several years.

Time scales

232. When the sediment transport rate in a movable-bed model is low, one way of alleviating the problem is to lengthen the time of the model operation to obtain enough bed change. This becomes difficult

when the modeling time scale for the sediment transport determined by this method varies in different areas of the model. This appears to be the case in the Galveston Harbor entrance model. The model year was determined somewhat arbitrarily. As discussed in paragraph 79, the model year covered 7 hr of model operation, giving a sedimentation time scale of about 1:1251 (7 hr model = 1 year prototype). The model verification test of the general bed condition covered seven model years. The changes in that 7-year period compared well with prototype changes occurring over a 10-year period. The prototype changes during the 10-year verification period could have occurred in a much shorter period, but 10 years is considered a representative period for this discussion. The model time scale defined by the bed changes for the movable bed was on the order of 1:1788 (49 hr model = 10 year prototype), relating the model 7-year period to the 10-year prototype period. Based on the volume of material shoaling in the model channel during the 7-year verification test (model year arbitrary), the model shoaling time scale is much smaller. The model average shoaling during each model year, still arbitrary, was 901,000 cu yd, while the prototype shoaling was approximately 1,183,000 cu yd. Assuming that the model operation time defining a model year could have been prolonged to increase model shoaling to the point where the dredging requirement would be the same as in the prototype, the model channel shoaling time scale would have been approximately 1:953 (9.2 hr model = 1 year prototype).

233. Based upon the large difference in Δ_{F_*} values for tidal currents and waves, separate time scales for transport by these two mechanisms appear likely. The model operating technique provided for separate scales by having a shorter period of waves than of tidal currents, resulting in a composite time scale accounting for both.

234. A sediment transport time scale is difficult to quantify when it is apparently variable for the transport through the inlet. The sediment transport time scale can be qualitatively tied to the scale effects reflected in the value of the particle densimetric Froude number, F_* . If the value of Δ_{F_*} is very low the model transport will be low and the time scale will be large and will require a relatively long

model operation period, while a higher value of Δ_{F_*} will require a shorter model operating time. The complicating factor is that the value of Δ_{F_*} varies through the inlet. In the outer portions of the inlet where waves are an important transport mechanism, Equation 8 would be appropriate for defining the shear velocity and the value of Δ_{F_*} would be larger than in the throat of the inlet where tidal currents are of greater importance and Equation 7 is used for the shear velocity. However, by having the prolonged periods in the model operation with maximum current velocities and no waves, the model is producing during those periods sediment transport in the areas where tidal currents are of importance (i.e., the inner bar) and having only minor transport in the areas of the bed where wave action is most important to the transport (approach channel and adjacent beaches). Within a model year of operation the tidal transport would have been possible throughout the year, while the wave transport would have only been possible 30 percent of the time. This difference tends to offset the discrepancy in the Δ_{F_*} values for tidal currents and for tidal currents with waves.

Storm effects

235. The effects of northers on sediment transport within the inlet is not well defined. Wind-induced setup would increase the capacity of the inlet to move sediment out without simultaneously overloading it with a large littoral transport. Northers will certainly supply large volumes of fine sediment to the inlet, but the increased current velocities would probably prevent rapid deposition of this sediment. Northers are a frequent winter occurrence in Texas, so their effects might be expected to be reproduced with an average hydraulic condition in the model; however, a specific simulation could easily be included in a model test. The Galveston model verification procedure may have included such a simulation in the prolonged maximum flows.

236. Tropical storm effects on the inlet are more varied than those of northers. The results of Hurricane Carla show that tropical storms can have a significant effect on the inlet hydrography, but those effects will be dependent upon a storm's duration, intensity, proximity, and direction of approach. Storms moving ashore near Galveston, such as

Carla, provide increased sediment load due to an enlarged littoral transport and an increased capability to move sediment by waves and storm surge. Beach and jetty overtopping allows localized deposit of large sediment volumes. More distant storms increase littoral transport by their waves without substantially increasing transport power in the inlet. Both can result in unusually heavy shoaling volumes in the navigation channel.

237. It should be much more difficult to include an average tropical storm effect in the model because of the drastic effect that one storm may have. In the verification test, the scarcity of prototype data did not encourage any attempt to include a storm effect and subsequent readjustment. The relatively short time spans of the verification and postconstruction periods did not permit averaging of a once-in-10-years storm nor did they share an equal occurrence of storms (Table 19). Because of inconstant and uncertain storm effects, the degree of agreement between model and prototype should not be expected to be precise.

Similarity of bed conditions

238. The model plan tests were run using the 1960 bed conditions as a starting condition. As described in paragraphs 161-169, this was a fairly accurate representation of the prototype bed condition just prior to construction in 1967. The major difference was that the prototype had a somewhat greater cross-sectional area between the tips of the jetties and in the area of the south jetty sand spit.

239. During construction, some of the model and prototype dredged material was deposited in the old outer bar channel. After completion of construction, the model maintenance volumes continued to be deposited there; but in the prototype, part of the material was hauled to offshore disposal sites. This difference in procedure could have affected the model either by some of the disposed material moving back into the channel or by constricting the cross section. Plates 66 and 67 show that the cross section through the outer bar was somewhat different in model and prototype, with the model shallower in the disposal area and deeper on the opposite side of the realigned channel.

240. Another difference in model and prototype bed conditions that might have affected model results was the dredging of the prototype anchorage basin. The anchorage basin design constructed in the prototype was not tested in the model and was not included in the construction procedure test from which these data were drawn. One anchorage basin tested was somewhat similar to that which was constructed, and those test results showed that continued maintenance of the anchorage basin would slightly decrease maintenance volumes for the navigation channel.

Evaluation of Results

241. In an effort to better understand the model performance, results of the comparison of the model predictions with the postconstruction prototype observations need to be discussed in light of the modeling techniques employed during the model study.

242. In summary, results of the comparisons between the model and prototype postconstruction data show that:

- a. The general locations of zones of deeper or shallower depths in the navigation channel were fairly accurately predicted by the model.
- b. Scour and fill in the model navigation channel were on a much smaller scale than were the changes observed in the prototype navigation channel.
- c. The model inner bar channel predicted progressive channel scour throughout the test, while the prototype scour and fill tended to offset one another.
- d. The model's predictions of dredging volumes for the outer bar channel were substantially correct in both absolute and relative terms.
- e. The model's predictions of absolute dredging volumes for the approach channel were too low and the relative changes were somewhat low.
- f. The model prediction for the distribution of shoaling over the three channel sections was incorrect, primarily due to a lack of shoaling in the model inner bar channel.
- g. The total average shoaling volume for the entire entrance channel after construction was approximately twice the volume predicted by the model tests.

_h_. The model predictions for the general areas of scour and fill in the bed between the jetties were fairly accurate.

_i_. The specific locations of small zones of scour and fill were not accurately predicted by the model.

Inner bar channel

243. The sediment transport rate in the inner bar channel, where tidal currents are the primary transport mechanism, would be expected to be low because of low Δ_{F_*} values. Since the model inner bar channel exhibited progressive scour, it is obvious that transport did occur but that the sediment supply was less than the transport capability. It has already been suggested that the verification wave should have resulted in too little sediment entering the inlet from the ocean side. A second major source of sediment is that material already in the inlet which is rearranged by crosscurrents that are either direct tidal currents or secondary currents generated by inlet geometry. If the primary tidal current transport capacity were low, that of the crosscurrents would almost certainly be low, too. It has also been said that the sediment supply from the bay would have been low in the model although the relative contribution to shoaling volumes from this source is uncertain.

244. The next question to consider in evaluating the model inner bar channel is whether the scour zone in that area is a consistent prototype feature or not and if so, did the model reproduce its location correctly. The 1950 to 1960 bed change map (Plate 12) showed the scour zone somewhat closer to the south jetty than was reproduced in model verification (Plate 13). The 1950 to 1962 map (Plate 75) shows it to be very slightly northward of the 1950 to 1960 position, whereas in the 1960 to 1962 map (Plate 74) the scour zone is very close to its position in the model. In the postconstruction period (Plates 71 and 73), the zone is observed to be at different intermediate positions between the 1950 to 1960 and model verification positions. It can be concluded that for the periods of interest the scour zone was a persistent feature of the entrance but that the area of greatest scour moved laterally back and forth. Such a persistent (23 years) scour implies that a substantial inlet readjustment is occurring and the deepening probably does not

represent readjustment to repeated storm-induced perturbations in the bed. The conditions do not exclude a slow readjustment to a single large perturbation.

245. Despite the 23-year deepening trend just south of the new channel alignment, the postconstruction period saw repeated annual dredging of the inner bar channel, though the volumes were not large. This can be explained by examining the channel condition maps (Plates 15-38). As described in paragraph 141, shoaling in the inner bar channel was confined to the north side and seaward end of the channel. The bay end and the south side of the channel remained fairly stable near project depth, and the principal scour zone was between the channel and south jetty. Relatively minor shifts in the shoaling zones could have made the inner bar channel nearly self-maintaining.

246. The prototype inner bar area has a fairly substantial amount of silt-and-clay material. It is possible that the composition of bed material there is stabilized by the finer materials, becoming more resistant to scour and allowing for accelerated shoaling rates. This phenomenon could, of course, not be duplicated in the modeling efforts.

Outer bar channel

247. In the outer bar channel the prototype dredged volumes (Table 11) were in general agreement with model predictions. This occurred in spite of an initial massive overdredging in the prototype and the previously noted low sediment supply in the model. When adjusted for underdepth and overdepth the dredged volumes were even closer (Table 15). With required dredging volumes (Table 16) fairly close and hydrographic changes between dredgings (Table 13) about four times larger in the prototype, it appears that the overdredged portion may be slowly filling with sediment.

248. The channel condition maps (Plates 15-38) show the same pattern of a shallow south side and a deeper north side of the outer bar channel in both model and prototype. This, in combination with differences in hydrographic changes (Table 13) and channel scour-and-fill patterns (Plates 39-50), indicates that the model outer bar channel performed similarly to the prototype but with the relative magnitudes of

changes much too small in the model. Since both scour and fill were low in the model, the net result was that dredging requirements were in fairly close agreement with the prototype.

249. The conditions described above imply that the model outer bar channel results were in reasonable agreement with the prototype because the trends of scour and fill were correctly reproduced and because a low sediment transport capability was compensated by a low sediment supply and an appropriate time scale.

Approach channel

250. The reported dredged volumes (Table 11) for the approach channel show the model to have about half the average annual volume of the prototype. In the other volume computations the disparity is even greater. The scour-and-fill maps (Plates 39-50) show that the only portion of the model approach channel that shoaled substantially was that at the tips of the jetties, whereas the prototype channel shoaled over most of its length. This also was the result of an inadequate sediment supply. Had the verification wave been from a different direction or possibly had a longer period, more shoaling would have occurred in the outer portion of the approach channel. It is significant that deepening the channel by 4 ft required extending it about a mile into a part of the model that had not been verified.

Comparison with Verification

251. If the discrepancies between model and prototype are to be explained by low sediment supply, low sediment transport capacity, and inexact location of scour-and-fill zones, then the model verification must be explained in those terms as well.

252. The model verification resulted in generally accurate reproduction of scour-and-fill patterns. Precise reproduction was not considered necessary and was not obtained. This tendency to reproduce general patterns was also observed in the postconstruction period and in some areas resulted in accurate model prediction; accurate predictions did not occur in the inner bar channel, where a slight difference

in location of the scour zone caused the prototype channel to experience locally heavy shoaling not predicted by the model.

253. The outer bar channel, which was altered less drastically by the channel realignment, gave the best results for the postconstruction period. Model scale effects tended to compensate for each other during both the preconstruction and postconstruction periods.

254. The inner bar channel was changed considerably by the realignment. It was moved from an area of overall deposition to an area of both scour and fill. It was thus afflicted by two changes--location in an area where imprecision in patterns could have significant effects, and location in a scour area where the deficiencies of low sediment supply and low transport rates might not compensate for each other.

255. For the verification tests, the prototype data for the approach channel were included in a total volume for outer bar and approach channels; therefore the model's deficiences, if any, might be masked by the outer bar channel. Extension of the approach channel altered that channel's contribution in two ways--the navigation channel was extended into a section of the model that had not been thoroughly verified, and the approach channel's contribution to the overall dredged volumes was increased by an increase in area to dredge. The model approach channel seems to have retained verification test reliability in the landward portion.

256. While this analysis implies that the sediment supply to the inlet was low due to the orientation and possibly the characteristics of the verification wave, it has also been noted that more oblique (and thus more effective in producing littoral transport) waves were tried in the verification trials but proved unsatisfactory. In the absence of data from these trials the cause cannot be determined, but it is possible that waves other than those chosen for verification would be incapable of reproducing prototype behavior.

PART VI: CONCLUSIONS

Model Predictions

257. The Galveston Harbor entrance model's predictions are first judged for how well they satisfied the study objectives as given by paragraph 9. It is concluded that for the 6 years following construction the model results:

- a. Correctly predicted that the channel realignment and dredged material disposal halted undermining of the north jetty next to the outer bar channel.
- b. Correctly predicted that total maintenance dredging volumes would increase for the proposed channel but underpredicted the magnitude of that increase.
- c. Erroneously predicted that the inner bar channel would experience net erosion and require no maintenance dredging beyond the second year.
- d. Correctly predicted the approximate absolute and relative increases in maintenance dredged volumes for the outer bar channel.
- e. Correctly predicted that maintenance dredging volumes for the approach channel would increase, but severely underpredicted the magnitude of that increase due to a marked absence of shoaling in the seaward extension of the approach channel.
- f. Correctly predicted a seaward shift in the channel shoaling volume distribution but overpredicted the magnitude of the shift. This overprediction was due to the erroneous scour prediction for the inner bar channel.

It is therefore concluded that the model satisfied most of its qualitative objectives but failed to accurately meet most of its stated quantitative objectives.

258. The model's predictions of bed configuration changes within the jetties were fairly accurate representations of the changes experienced in the prototype but erred in the magnitude and precise location of the changes. Some bed feature changes could not be modeled because of differences in model and prototype dredging and disposal practices, the construction of the prototype anchorage basin, and an inability to define effects of singular events such as storms.

259. Discrepancies in model maintenance dredging volume predictions are believed to have been primarily due to:

a. A low rate of sediment supply to the inlet.

b. Low tidal current transport capacity.

c. Inexact location of some scour-and-fill areas.

Shoaling volumes in the outer bar channel and landward portion of the approach channel were more accurately predicted because the low sediment supply rate and low transport rates offset one another and those channels were not in zones where the boundaries between scour and fill significantly affected dredged volumes.

260. The inner bar channel results were incorrect due to a deficient sediment supply and an inaccurate model representation of the scour zone through which the channel passes. It is possible that wind-blown sand and bay sediments not reproduced in the model may be significant sources of shoaling material in the inner bar channel. The lateral location of the scour zone was somewhat erroneous, but more important to the shoaling volumes, it extended too far seaward in the model.

261. The outer portion of the model approach channel failed to shoal properly because the model wave crest was nearly perpendicular to the channel axis and thus did not move sediment across the channel. Another possible reason is that the single model wave period did not adequately transport sediment in deeper water.

262. The low sediment transport capacity was caused by a sediment that was too large and/or too heavy to be moved easily by scaled currents. The model-to-prototype ratio of particle densimetric Froude number (Δ_{F_*}) appears to have been a good indication of a low sediment transport capacity. The values of Δ_{F_*} due to waves were significantly higher than those due to tidal currents, and this is reflected in better model performance in those areas where waves were a more important part of the transport process except in deep water where the model wave did not effectively move sediment into the approach channel.

263. Low sediment supply from the littoral zone was a direct requirement of the model's low transport capacity. The single wave from the southeast did not reproduce a large gross littoral transport and

therefore balanced the model's low transport capacity. A greater sediment supply would have clogged the model inlet. In deeper water, the direction and period of the wave may have prevented adequate transport into the approach channel.

264. The pre- and postconstruction periods were not long enough to average the effects of tropical storms, but the storm frequencies and locations for the two periods were not sufficiently dissimilar to cause severe changes in shoaling volumes. Differences in storm conditions could have had an effect on location and extent of some scour-and-fill zones during the study period. In particular, if a storm during the study period were to wash beach sand over the south jetty and deposit it on the spit adjacent to the inner bar channel, then significant differences in inner bar shoaling could result.

265. Distortion of tidal current similitude was a necessary procedure to obtain adequate sediment transport in the inner portion of the entrance. Prolongation of the maximum flows improved the transport capacity of the tidal currents but may have prevented sufficient trapping of littoral material by creating sustained unidirectional flow that flushed material from the inlet rather than moving it back and forth in a reversing flow.

266. From this analysis of the Galveston Harbor entrance model, it is concluded that movable-bed modeling of similar inlets is a feasible, though difficult, technique for the solution of sedimentation problems. Infallible movable-bed techniques are not available to the modeler, but if they were, they might be too costly to be useful. Movable-bed model studies should be judged by the quality of their results in comparison with the quality and quantity of available prototype data, the effort required to conduct the model study, and the limitations of other prediction methods.

Recommendations

267. There is an inherent danger in applying results from one movable-bed inlet model to others with differing characteristics, but

knowledge of coastal sediment transport processes may be combined with observations from the Galveston Harbor entrance model to recommend and reaffirm some practices that will improve model reliability. This list is not complete in that it addresses only those situations encountered in this model study.

- *a*. Prototype data should be the modeler's first concern. The data should be accurate, comprehensive, and in sufficient detail to permit a thorough understanding of the sedimentary processes of the inlet. These data should consist not only of bed surveys and dredging volumes but should include documentation of typical hydrodynamic and climatic conditions as well as those of the survey periods. Sediment supply sources should be identified. It must be recognized however, that an adequate prototype data base is a rare exception.

- *b*. The movable-bed material should be chosen to permit transport by currents that are as close as possible to scaled conditions. The value of the model-to-prototype densimetric particle Froude number ratio appears to be a good indication of what the sediment characteristics should be, but strict equality in model and prototype is probably unnecessary. Model length scales should be chosen that permit realistic sediment transport rates of a practical model sediment. Available model sediments and their cost will dictate what degree of similitude is feasible.

- *c*. Hydrodynamic similitude should be the starting point in shoaling verification. Distortion of hydrodynamic conditions may be permissible but should be minimized. Wave climate should be reproduced by a representative set of waves that provide for a range of wave periods, heights, and directions. Choosing representative waves also requires a sound data base.

- *d*. Model operation should be designed to ensure that important sediment sources are represented and that sediment supply and transport capacity are in the proper relation for each area of interest. If prototype data indicate the necessity of including singular events such as storms, an attempt should be made to simulate them as singular events in the model. Defining storm effects is likely to be more difficult than reproducing them in the model.

- *e*. Model results must be interpreted in the light of verification accuracy and tempered by attention to the magnitude of the alterations to the inlet. The practice of interpreting model shoaling in terms of relative change

rather than absolute volumes is a sound one. This is true not only because such interpretations are more reliable, but also because they prevent the user of model results from applying too literal an interpretation of shoaling volume predictions. Available resources of data, time, and money dictate the level of modeling effort and quality of model results.

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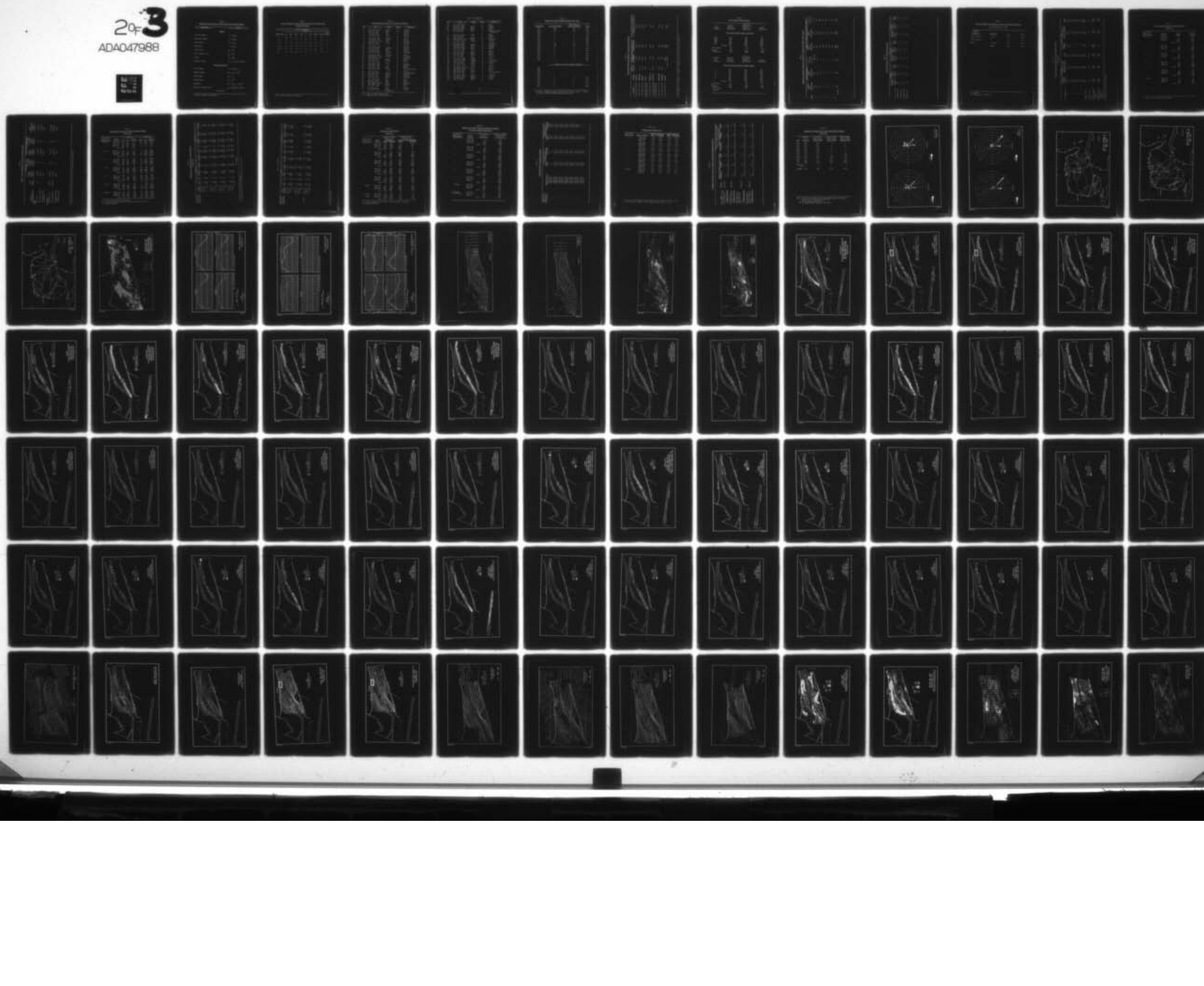


Table 1

Hydraulic Scale Relations for Distorted-Scale Coastal Models

Parameter*	Scale
General	
Vertical length	$Y_r = Y_m/Y_p$
Horizontal length	$X_r = X_m/X_p$
Bottom slope	$S_r = Y_r/X_r$
Distortion	$n = Y_r/X_r$
Surface area	$A_{sr} = X_r^2$
Cross-sectional area	$A_{cr} = X_r Y_r$
Volume	$V_r = X_r^2 Y_r$
Hydraulic radius	$R_r = Y_r$ (wide channels)
Tides and Currents	
Froude number	$F_r = u_r/Y_r^{1/2} = 1$
Reynolds number	$Re_r = u_r Y_r = Y_r^{3/2}$
Tidal height	$H_r = Y_r$
Current speed	$u_r = Y_r^{1/2}$
Discharge	$Q_r = u_r X_r Y_r = X_r Y_r^{3/2}$
Effective roughness size	$k_{sr} = Y_r^4 S_{er}^3/u_r^6 = Y_r^4/X_r^3$

(Continued)

* Notation defined in Appendix A.

Table 2

Percent Frequency of Wave Height and Period, Galveston Area

1969-1970 Averages

	Percent Frequency								
	Height, ft								
Period, sec	<1	1-2	3-4	5-6	7	8-9	10-11	12-16	Mean Height
<6	8.5	22.1	21.1	7.2	1.7	0.7	0.2	0.1	3
6-7	0.4	2.3	7.0	7.4	3.0	1.3	0.4	0.3	5
8-9	0.1	0.4	0.9	1.6	1.2	0.6	0.4	0.3	6
10-11	0.0	0.6	0.3	0.3	0.4	0.3	0.2	0.2	6
12-13	0.0	0.0	0.2	0.1	0.1	0.1	0.1	0.0	7
>13	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.2	10

Note: Source of data, Reference 18.

Table 3

Tropical Storms in the Gulf of Mexico, 1950-1973

No.	Date	Name	Class*	Landfall
1	Aug 27-31, 1950	Baker	H	Alabama
2	Sep 3-7, 1950	Easy	H	Florida
3	Oct 1-4, 1950	How	T	Mexico
4	Oct 8-10, 1950	Item	H	Mexico
5	Oct 17-21, 1950	Love	H	Florida
6	Aug 20-22, 1951	Charlie	H	Mexico
7	Sep 20-21, 1951	George	T	Mexico
8	Sep 29-Oct 2, 1951	How	T	Florida
9	Jun 1-6, 1953	Alice	T	Florida
10	Aug 28-30, 1953	--	T	Florida
11	Sep 14-20, 1953	--	T	Florida
12	Sep 24-28, 1953	Florence	H	Florida
13	Oct 7-9, 1953	Hazel	T	Florida
14	Jun 24-26, 1954	Alice	H	Mexico
15	Jul 27-29, 1954	Barbara	T	Louisiana
16	Sep 11-12, 1954	Florence	H	Mexico
17	Jul 31-Aug 2, 1955	Brenda	T	Louisiana
18	Aug 25-29, 1955	--	T	Louisiana
19	Sep 4-6, 1955	Gladys	H	Mexico
20	Sep 17-19, 1955	Hilda	H	Mexico
21	Sep 28-29, 1955	Janet	H	Mexico
22	Jun 11-14, 1956	--	T	Louisiana
23	Jul 25-26, 1956	Anna	H	Mexico
24	Sep 10-12, 1956	Dora	T	Mexico
25	Sep 22-25, 1956	Flossy	H	Louisiana/Florida
26	Jun 8-9, 1957	--	T	Florida
27	Jun 25-28, 1957	Audrey	H	Texas/Louisiana
28	Aug 8-11, 1957	Bertha	T	Louisiana
29	Sep 7-8, 1957	Debbie	T	Florida
30	Sep 16-19, 1957	Ester	T	Louisiana
31	Jun 14-16, 1958	Alma	T	Mexico
32	Sep 3-6, 1958	Ella	H	Texas
33	May 28-Jun 2, 1958	Arlene	T	Louisiana
34	Jun 15-18, 1959	Beulah	T	Mexico
35	Jul 22-25, 1959	Debra	H	Texas
36	Oct 6-8, 1959	Irene	T	Alabama
37	Oct 17-18, 1959	Judith	H	Florida

(Continued)

Note: Source of data, Reference 21.

* Hurricane (H), Tropical storm (T).

Table 3 (Concluded)

No.	Date	Name	Class	Landfall
38	Jun 22-28, 1960	--	T	Texas
39	Sep 9-11, 1960	Donna	H	Florida
40	Sep 14-16, 1960	Ethel	H	Alabama
41	Sep 8-12, 1961	Carla	H	Texas
42	Nov 4-8, 1961	Inga	T	Stayed off coast of Mexico
43	Sep 16-19, 1963	Cindy	H	Texas
44	Jun 2-11, 1964	--	T	Florida
45	Aug 5-8, 1964	Abbey	H	Texas
46	Sep 30-Oct 4, 1964	Hilda	H	Louisiana
47	Oct 13-15, 1964	Isbell	H	Florida
48	Jun 12-15, 1965	--	T	Florida
49	Sep 8-10, 1965	Betsy	H	Louisiana
50	Sep 26-30, 1965	Debbie	T	Alabama
51	Jun 8-10, 1966	Alma	H	Florida
52	Sep 20-21, 1966	Hallie	T	Mexico
53	Oct 5-11, 1966	Inez	H	Mexico
54	Sep 17-22, 1967	Beulah	H	Texas
55	Oct 1-4, 1967	Fern	H	Mexico
56	Jun 2-5, 1968	Abbey	H	Florida
57	Jun 22-24, 1968	Candy	T	Texas
58	Oct 16-19, 1968	Gladys	H	Florida
59	Aug 15-19, 1969	Camille	H	Mississippi
60	Oct 1-6, 1969	Jenny	T	Florida
61	Oct 19-27, 1969	Laurie	H	Mexico
62	Jul 19-23, 1970	Becky	T	Florida
63	Jul 31-Aug 5, 1970	Celia	H	Texas
64	Sep 10-13, 1970	Ella	H	Mexico
65	Sep 14-17, 1970	Felice	T	Texas
66	Sep 3-13, 1971	Fern	H	Louisiana/Texas
67	Sep 11-17, 1971	Edith	H	Louisiana
68	Jun 14-20, 1972	Agnes	H	Florida
69	Aug 18-22, 1973	Brenda	H	Mexico
70	Sep 1-7, 1973	Delia	T	Texas

Table 4

Reported Prototype Dredged Volumes, 1000 cu yd

Fiscal Year	Inner Bar Channel	Outer Bar and Approach Channels	Total
1950	1839	383	2222
1951	472	728	1200
1952	*	*	332
1953	*	*	639
1954	*	*	1318
1955	*	*	1106
1956	*	*	891
1957	507	794	1301
1958	515	0	515
1959	*	*	1053
1960	*	*	1677
1961	*	*	907
1962	*	*	2148
1963	*	*	2504
1964	0	0	789
	Construction of New Channel Alignment		
1965			
1966			
1967			
1968			
1969	*	*	1355
1970	*	*	2277
1971	*	*	1910
1972	*	*	3150
1973	*	*	1893

* Source: Volumes for 1950 to 1959 from OCE Annual Report.[9] Volumes for 1960 to 1973 from hopper dredge report sheets.

Table 5

Prototype Channel Realignment Construction Dredging

Period	Dredge	Channel Sections*	Dredge Volume, 1000 cu yd Realignment	Dredge Volume, 1000 cu yd Anchorage Basin	Volume Deposited in Abandoned Channel, 1000 cu yd
14 Dec 64-27 Mar 65	*Harding*	1	1,330	None	None
2 Mar 65- 3 Aug 65	*MacKenzie*	1,2,3	2,279	None	None
3 May 65-24 Nov 65	*Jahncke*	2,4,5	4,147	None	1332
30 Oct 65- 2 Jan 66 23 Feb 66-28 Feb 66	*Gerig*	1,6,3	2,112	None	445
13 Feb 66-14 Mar 66	*MacKenzie*	1,6	669	None	431
13 Oct 66-13 Nov 66 2 Dec 66- 4 Dec 66 25 Dec 66-12 Feb 67	*MacKenzie*	1,6,3	1,362	None	1156
10 Apr 67- 4 Oct 67	*McFarland*	1,6,3	3,645	None	429
23 Jan 68-28 Mar 68	*MacKenzie*	2,4,5	996	1236	2052
18 Dec 66-25 May 68	*Gahagan*	--	None	3555	
		Total	16,540	4791	5845

* See Figure 3 for location of channel construction sections; source, Reference 22.

Table 6

Verification Dredged Volumes

Fiscal Year		Inner Bar Channel, 1000 cu yd	Outer Bar and Approach Channels, 1000 cu yd	Total, 1000 cu yd
Prototype Dredged Volumes, 1957-1961				
1957		291	303	594
1958		468	307	775
1959		222	1614	1836
1960		698	84	782
1961		581	1347	1928
	Average	452	731	1183
Distribution		38%	62%	100%
Maximum variation		+54% -51%	+121% -88%	+63% -50%

Sequence No., Year		Inner Bar Channel, 1000 cu yd	Outer Bar and Approach Channels, 1000 cu yd	Total, 1000 cu yd
Model Verification Scaled Dredged Volumes				
1		588	861	1449
2		266	910	1176
3		352	1167	1520
4		190	255	445
5		232	435	667
6		140	423	563
7		237	250	487
	Average	286	614	901
Distribution		32%	68%	100%
Maximum variation from 7-year average		+106% -51%	+90% -59%	+69% -51%

Table 7

Comparison of Model Dredging Volumes for Initial and Repeat Plan 2 Tests

	Inner Bar Channel			Outer Bar Channel and Approach Channel		
Year	Initial Test, 1000 cu yd	Repeat Test, 1000 cu yd	Variation %	Initial Test, 1000 cu yd	Repeat Test, 1000 cu yd	Variation %
1	416	379	-9	2121	1852	-13
2	307	320	+4	1724	688	-60
3	0	92	--	623	1226	+97
4	0	0	--	369	567	+54
5	0	0	--	1016	1235	+21
6	0	0	--	461	444	-4
7	0	0	--	802	926	+15
8	0	0	--	1600	445	-72
Average	90	99	+10	1090	923	-15

Table 8

Model Verification of Current Velocities

	Sta B-2			Sta C-2			Sta F-3		
	Prototype Velocity fps	Model Velocity fps	Ratio P/M	Prototype Velocity fps	Model Velocity fps	Ratio P/M	Prototype Velocity fps	Model Velocity fps	Ratio P/M
Average flood	0.6	0.4	1.4	2.5	2.3	1.1	2.3	1.7	1.3
Average ebb	0.6	0.4	1.4	1.6	1.4	1.1	1.8	1.1	1.6
Maximum flood	1.3	1.1	1.2	4.3	4.0	1.1	4.0	3.3	1.2
Maximum ebb	1.0	0.7	1.4	2.5	2.3	1.1	3.0	1.8	1.7

Table 9

Possible Sediment Characteristic Scales for Model with Scales

$Y_r = 1:100$ and $X_r = 1:500$

Primary Transport Process	Equations	d_r	γ_r'
Tidal currents	5 and 7	4.5:1	1:89
Tidal currents	9	3.4:1	1:1*
Waves	5 and 8**	1.6:1	1:4.4
	Actual	12:1	1:4.2

* Assumed.
** Using k_{sr} from Table 1.

Table 10

Model Dredging Volumes for Base and Plan 2 Tests

1000 cu yd

Year	Base Test			Plan 2 Test*		
	Inner Bar Channel	Outer Bar and Approach Channels	Total	Inner Bar Channel	Outer Bar and Approach Channels	Total
1	369	560	929	416	2121	2537
2	341	462	803	307	1724	2031
3	319	498	817	0	623	623
4	180	643	823	0	369	369
5	233	569	802	0	1016	1016
6	179	512	691	0	461	461
7	173	682	855	0	802	802
8	262	569	831	0	1600	1600
Average, years 1-8	257	562	819	90	1090	1180
Average, years 3-8	224	579	803	0	812	812
Maximum variation from 8-year average	+44% -33%	+21% -18%	+13% -16%	+362% -100%	+95% -66%	+115% -69%
Maximum variation from 6-year average (years 3-8)	+42% -23%	+18% -14%	+6% -14%	+0 -0	+97% -55%	+97% -55%

* Without construction procedure.

Table 11

Postconstruction Reported Dredging Volumes

1000 cu yd

Year After Completion of Construction	Channel Section		Model* Volume	Prototype Volume
1	Inner bar		0	411
	Outer bar		500	212
	Approach		1200	635
		Total	1700	1258
2	Inner bar		0	773
	Outer bar		190	426
	Approach		440	1078
		Total	630	2277
3	Inner bar		0	967
	Outer bar		267	294
	Approach		326	649
		Total	593	1910
4	Inner bar		0	687
	Outer bar		362	529
	Approach		564	1934
		Total	926	3150
5	Inner bar		0	518
	Outer bar		181	383
	Approach		1026	992
		Total	1207	1893
Average	Inner bar		0	671
	Outer bar		300	369
	Approach		711	1058
		Total	1011	2098

* Plan 2 with construction procedure.

Table 12

Effects of Realignment on Reported Dredged Volumes

Model and Prototype Data	Years of Record	Inner Bar: Average Annual Dredging cu yd	Inner Bar: Percentage of Average Annual Dredging Total	Outer Bar and Approach: Average Annual Dredging cu yd	Outer Bar and Approach: Percentage of Average Annual Dredging Total	Total Average Annual Dredging cu yd
Model						
Base test	8	257,000	31	561,900	69	818,900
Realigned channel*	8	90,400	8	1,089,500	92	1,179,900
Percentage change from base		-65%	--	+94%	--	+44%
Prototype						
Preconstruction	1957-61	452,000	38	731,000	62	1,183,000
Postconstruction	1968-73	671,200	32	1,420,400	68	2,097,600
Percentage change from preconstruction		+48%	--	+94%	--	+77%

* Model data from plan test under normal base-test conditions (Table 10).

Table 13

Hydrographic Changes in Channel Between Dredgings

1000 cu yd

Years After Completion of Construction	Channel Section	Model*			Prototype		
		Scour	Fill	Net Change**	Scour	Fill	Net Change**
0 to 1	Inner bar	176	174	-2	26	1100	+1074
	Outer bar	14	465	+451	94	603	+509
	Approach	721	122	-599	†	†	†
	Total	911	761	-150	--	--	--
1 to 2	Inner bar	440	31	-409	6	1088	+1082
	Outer bar	310	11	-299	2	739	+737
	Approach	150	228	+78	83	2887	+2804
	Total	900	270	-630	91	4714	+4623
2 to 3	Inner bar	282	52	-230	25	1513	+1488
	Outer bar	96	253	+157	18	618	+600
	Approach	116	303	+187	5	1916	+1911
	Total	494	608	+114	48	4047	+3999
3 to 4	Inner bar	315	54	-261	168	343	+175
	Outer bar	34	169	+135	49	237	+188
	Approach	35	438	+403	197	1036	+839
	Total	384	661	+277	414	1616	1202
4 to 5	Inner bar	258	7	-251	151	417	+266
	Outer bar	27	235	+208	108	187	+79
	Approach	207	313	+106	49	799	+750
	Total	492	555	+63	308	1403	+1095
5 to 6	Inner bar	474	5	-469	1	1948	+1947
	Outer bar	188	91	-97	0	552	+552
	Approach	176	442	+266	36	1417	+1381
	Total	838	538	-300	37	3917	+3880
Average	Inner bar	324	54	-270	63	1068	+1005
	Outer bar	112	204	+92	45	489	+444
	Approach	234	308	+74	74	1611	+1537
	Total	670	566	-104	182	3168	+2986

* Plan 2 with construction procedure.

** Positive values are net fill; negative values are net scour.

† No data available.

Table 14

Hydrographic Changes in Channel During Dredging

1000 cu yd

Years After Completion of Construction	Channel Section	Model*					Prototype				
		Scour	Fill	Net Change**	Overdepth	Underdepth	Scour	Fill	Net Change**	Overdepth	Underdepth
1	Inner bar	0	0	0	355	427	1914	1	-1913	1636	66
	Outer bar	72	0	-72	17	599	781	27	-754	1084	19
	Approach	436	20	-416	95	768	2647	101	-2546	1207	222
	Total	508	20	-488	467	1794	5342	129	-5213	3927	307
2	Inner bar	0	0	0	611	247	922	49	-873	1547	169
	Outer bar	301	64	-237	105	108	537	3	-534	979	161
	Approach	219	0	-219	162	690	2230	8	-2222	764	396
	Total	520	64	-456	878	1045	3689	60	-3629	3290	726
3	Inner bar	0	0	0	794	185	1059	46	-1013	1032	180
	Outer bar	136	14	-122	157	184	300	102	-198	634	239
	Approach	165	0	-165	189	739	1260	90	-1170	308	729
	Total	301	14	-287	1140	1108	2619	238	-2381	1974	1148
4	Inner bar	0	0	0	1050	162	260	200	-60	1248	301
	Outer bar	127	9	-118	159	203	235	76	-159	568	200
	Approach	184	0	-184	172	953	813	240	-573	250	930
	Total	311	9	-302	1381	1318	1308	516	-792	2066	1431

(Continued)

* Plan 2 with construction procedure.
** Positive values are net fill; negative values are net scour.

Table 14 (Continued)

Years After Completion of Construction	Channel Section	Model					Prototype				
		Scour	Fill	Net Change	Overdepth	Underdepth	Scour	Fill	Net Change	Overdepth	Underdepth
5	Inner bar	0	0	0	1248	93	1433	25	-1408	2075	106
	Outer bar	77	8	-69	106	297	538	20	-518	963	126
	Approach	416	21	-395	217	691	760	99	-661	375	1105
	Total	493	29	-464	1571	1081	2731	144	-2586	3413	1337
6	Inner bar	0	0	0	1688	36	†	†	†	†	†
	Outer bar	126	89	-37	65	110	†	†	†	†	†
	Approach	287	13	-274	317	776					
	Total	413	102	-311	2070	922					
Average	Inner bar	0	0	0	958	192	1118	64	-1054	1508	164
	Outer bar	140	31	-109	102	250	478	46	-432	846	149
	Approach	285	9	-276	192	770	1542	108	-1434	581	676
	Total	425	40	-385	1252	1212	3138	218	-2920	2935	989

† No data available.

Table 15

Adjusted Dredging Volumes

1000 cu yd

Years After Completion of Construction	Channel Section	Dredging Volumes Adjusted for Underdepth		Dredging Volumes Adjusted for Overdepth and Underdepth	
		Model	Prototype	Model	Prototype
1	Inner bar	107	160	-1	-451
	Outer bar	904	165	934	-57
	Approach	156	635*	163	**
	Total	1167	960	1096	**
2	Inner bar	0	876	-436	965
	Outer bar	0	568	-389	673
	Approach	362	1252	293	1695
	Total	362	2696	532	3333
3	Inner bar	0	978	-246	1493
	Outer bar	342	372	290	717
	Approach	375	981	349	1439
	Total	717	2331	393	3649
4	Inner bar	0	808	-279	592
	Outer bar	381	490	379	556
	Approach	779	2135	795	2192
	Total	1160	3433	895	3340
5	Inner bar	0	323	-266	-504
	Outer bar	274	309	328	-86
	Approach	764	1167	564	1042
	Total	1038	1799	626	452
Average	Inner bar	21	629	-246	419
	Outer bar	380	381	308	361
	Approach	487	1234	433	1592
	Total	888	2244	496	2372
Percent of total	Inner bar	2%	28%	-49	18
	Outer bar	43%	17%	62	15
	Approach	55%	55%	87	67
	Total	100%	100%	100	100

* Figure unadjusted due to lack of previous year's soundings.
** No data available.

Table 16

Comparison of Model Dredged Volumes with Computed Prototype Dredging Requirements

Years After Completion of Construction	Channel Section		Model Dredging Volumes, 1000 cu yd	Prototype Dredging Requirements, 1000 cu yd
1	Inner bar		0	553
	Outer bar		500	512
	Approach		1200	2661
		Total	1700	3726
2	Inner bar		0	319
	Outer bar		190	336
	Approach		440	2865
		Total	630	3520
3	Inner bar		0	663
	Outer bar		267	321
	Approach		326	2703
		Total	593	3687
4	Inner bar		0	189
	Outer bar		362	331
	Approach		564	1994
		Total	926	2514
5	Inner bar		0	359
	Outer bar		180	287
	Approach		1026	1772
		Total	1206	2418
6	Inner bar		0	590
	Outer bar		111	270
	Approach		815	3128
		Total	926	3988
Average	Inner bar		0	446
	Outer bar		268	343
	Approach		729	2521
		Total	997	3310
Percentage distribution	Inner bar		0%	14%
	Outer bar		27%	10%
	Approach		73%	76%
		Total	100%	100%

Table 17

Average Depths in Navigation Channel

Years After Completion of Construction	Channel Section	Average Depth Before Dredging, ft		Average Depth After Dredging, ft	
		Model	Prototype	Model	Prototype
0	Inner bar	--	--	42.0	44.8
	Outer bar	--	--	43.4	46.7
	Approach	--	--	43.3	44.8
1	Inner bar	42.0	41.1	42.0	45.1
	Outer bar	41.7	44.7	42.0	47.7
	Approach	41.7	42.0	43.0	45.3
2	Inner bar	42.9	43.0	42.9	44.7
	Outer bar	43.0	45.0	44.0	46.9
	Approach	42.9	41.5	43.4	44.5
3	Inner bar	43.5	41.7	43.5	43.7
	Outer bar	43.4	44.6	43.9	45.4
	Approach	43.0	41.9	43.2	43.5
4	Inner bar	44.0	43.4	44.0	43.5
	Outer bar	43.4	44.7	43.8	45.3
	Approach	42.6	42.4	42.9	43.2
5	Inner bar	44.5	43.1	44.5	45.9
	Outer bar	43.1	44.7	43.3	46.8
	Approach	42.8	42.1	43.3	43.1
6	Inner bar	45.6	41.9	45.6	--
	Outer bar	43.8	44.8	43.9	--
	Approach	43.0	41.3	43.4	--

Table 18

Average Depth Changes,* ft

Years After Construction	Channel Section	Between Dredgings		During Dredgings	
		Model	Prototype	Model	Prototype
1	Inner bar	0.0	+2.4	0.0	-4.0
	Outer bar	+1.7	+2.0	-0.3	-3.0
	Approach	+1.6	+2.8	-1.3	-2.3
2	Inner bar	-0.9	+2.1	0.0	-1.7
	Outer bar	-1.0	+2.7	-1.0	-1.9
	Approach	+0.1	+3.8	-0.4	-3.0
3	Inner bar	-0.6	+3.0	0.0	-2.0
	Outer bar	+0.6	+2.3	-0.5	-0.8
	Approach	+0.3	+2.6	-0.2	-1.6
4	Inner bar	-0.5	+0.3	0.0	-0.1
	Outer bar	+0.5	+0.7	-0.4	-0.6
	Approach	+0.6	+1.1	-0.3	-0.8
5	Inner bar	-0.5	+0.4	0.0	-2.8
	Outer bar	+0.7	+0.6	-0.2	-2.1
	Approach	+0.1	+1.1	-0.5	-1.0
6	Inner bar	-1.1	+4.0	0.0	--
	Outer bar	-0.5	+2.0	-0.1	--
	Approach	+0.3	+1.8	-0.4	--
Average	Inner bar	-0.6	+2.0	0.0	-2.1
	Outer bar	+0.3	+1.7	-0.4	-1.7
	Approach	+0.5	+2.2	-0.5	-1.7

* Positive depth change is fill; negative depth change is scour.

Table 19

Frequency of Storms in Gulf of Mexico During Prototype Data Periods

Data	Period	Number of Storms in Gulf of Mexico			Number of Storms in Gulf of Mexico North of Latitude 25°N and West of Longitude 90°W		
		Hurricanes	Tropical	Total	Hurricanes	Tropical	Total
Verification of bed scour and fill	1950-1960	19	21	40	5	7	12
Average each year		1.7	1.9	3.6	0.5	0.6	1.1
Verification of channel shoaling	1957-1961	7	10	17	3	5	8
Average each year		1.4	2.0	3.4	0.6	1.0	1.6
Postconstruction verification of bed scour and fill	1965-1973	15	7	22	5	3	8
Average each year		1.7	0.8	2.4	0.6	0.3	0.9
Postconstruction verification of channel shoaling	1968-1973	10	5	15	3	3	6
Average each year		1.7	0.8	2.5	0.5	0.5	1.0

Table 20

Comparison of Reported Prototype Maintenance Dredging

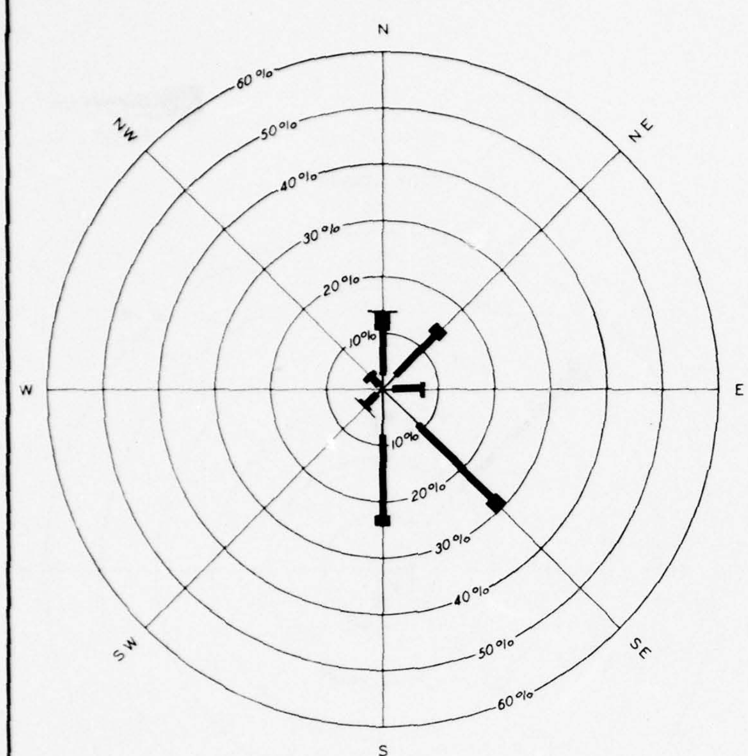
1000 cu yd

Year	Supplied By District*	From OCE Annual Reports, Fiscal Year	Hopper Dredge Report Sheets, Fiscal Year	Hopper Dredge Report Sheets, Calendar Year
1953	1076	639	--	--
1954	754	1318	--	--
1955	1065	1106	--	--
1956	1237	891	--	--
1957	594	1300	--	--
1958	775	515	--	556
1959	1836	1053	556	1585
1960	782	**	1677	999
1961	1928	907	907	1691
Total No. of Years	9	8	3	4
Average	1116	966	1047	1208

Note: Dashes (--) indicate that hopper dredge report sheets (Form No. 27) were not used prior to FY 59.

* Used for model verification.

** No volume figures quoted in 1960 report.



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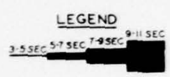
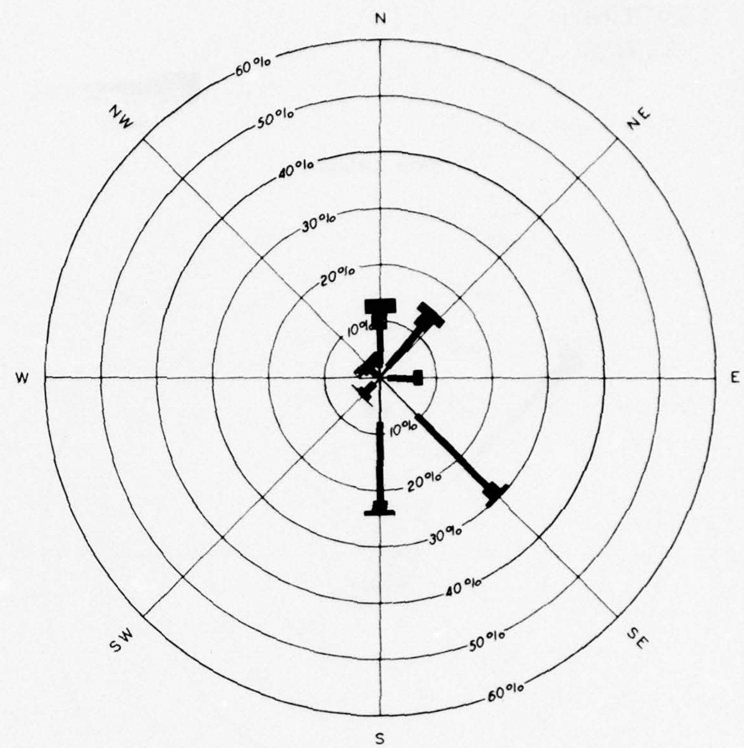
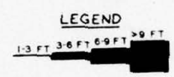
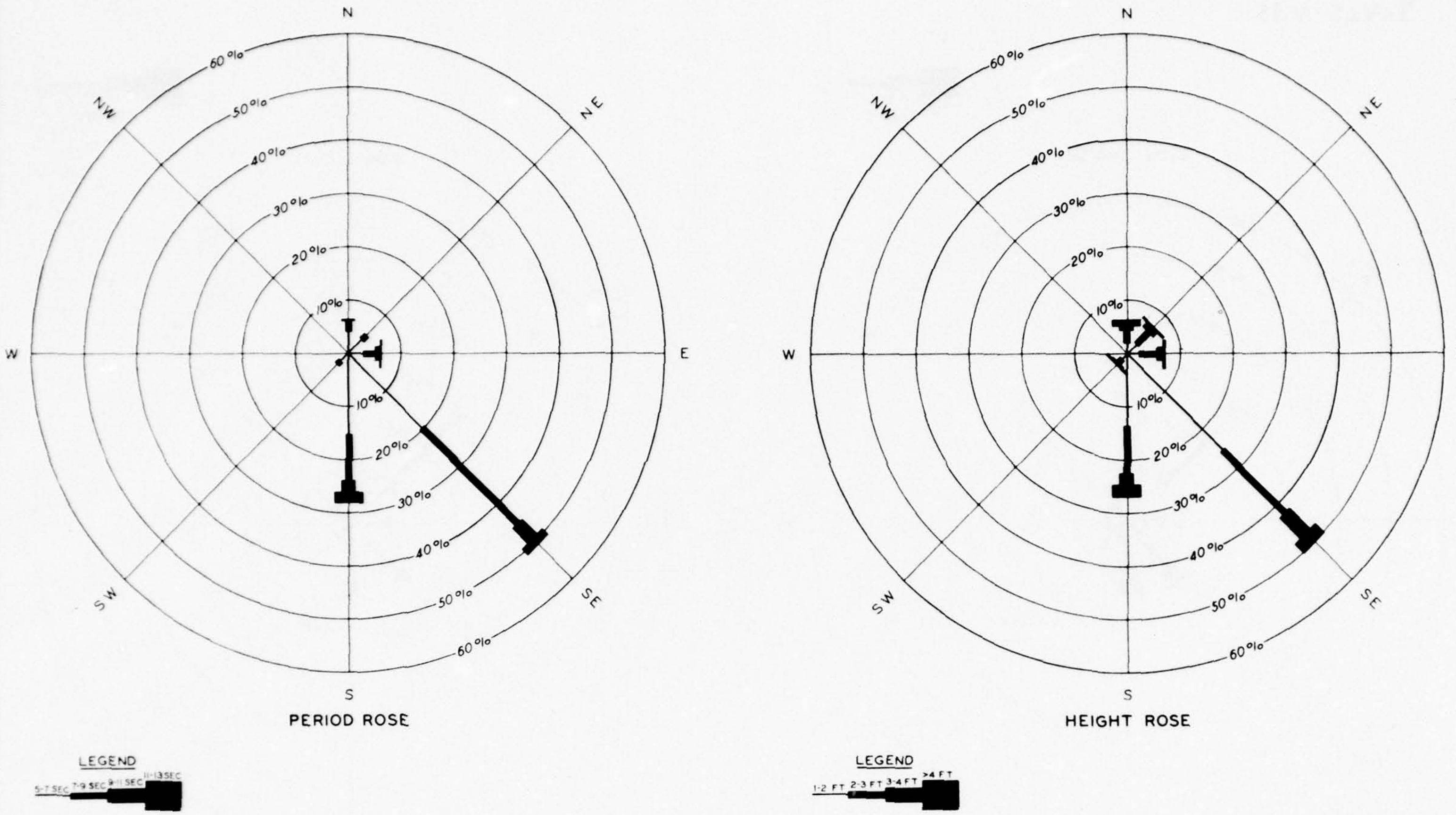




HEIGHT ROSE



SEA STATE
HINDCAST



SWELL
HINDCAST

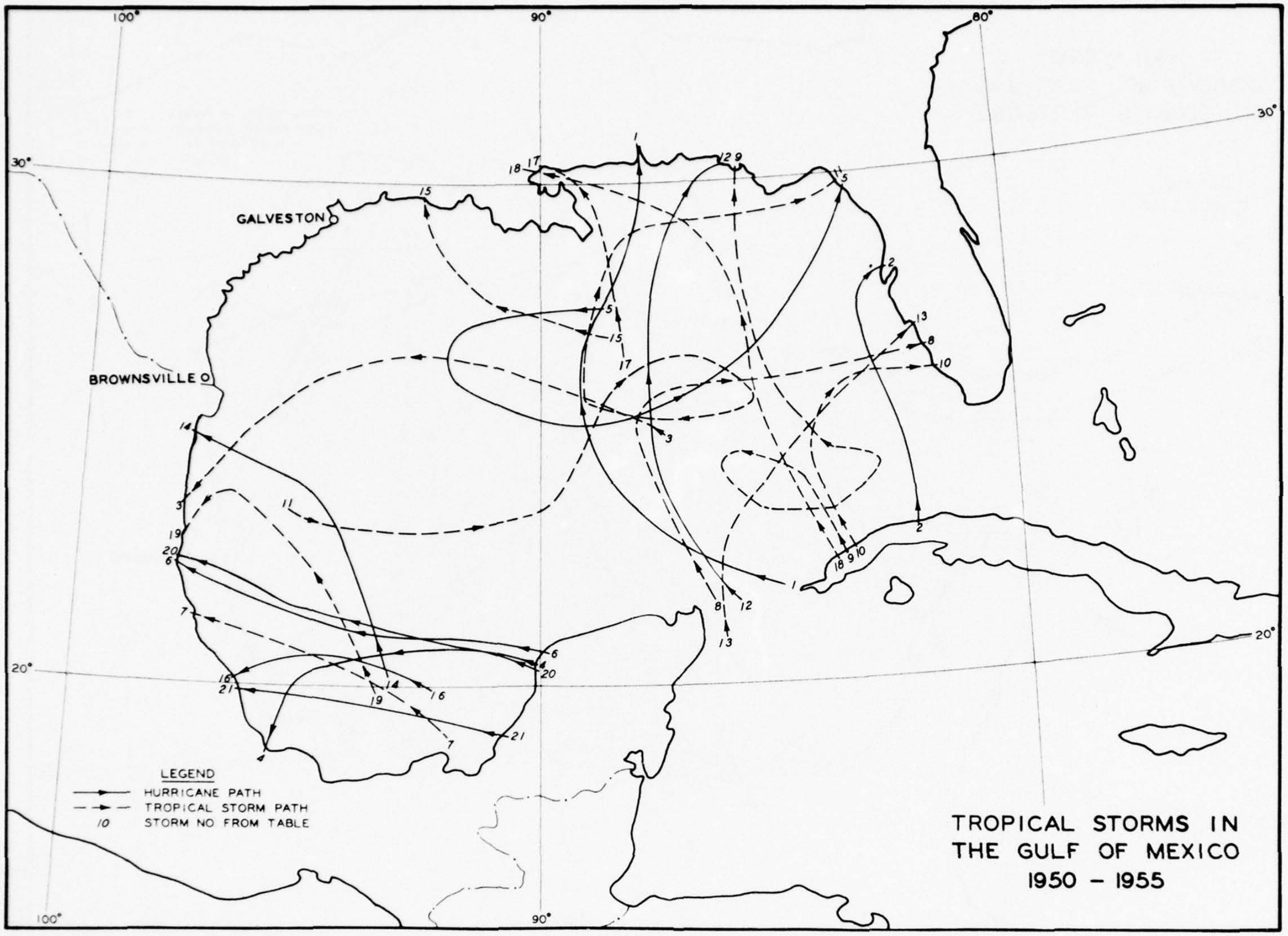

TROPICAL STORMS IN
THE GULF OF MEXICO
1950 - 1955
LEGEND
HURRICANE PATH
TROPICAL STORM PATH
10 STORM NO FROM TABLE
GALVESTON
BROWNSVILLE
100°
90°
80°
30°
20°

PLATE 3

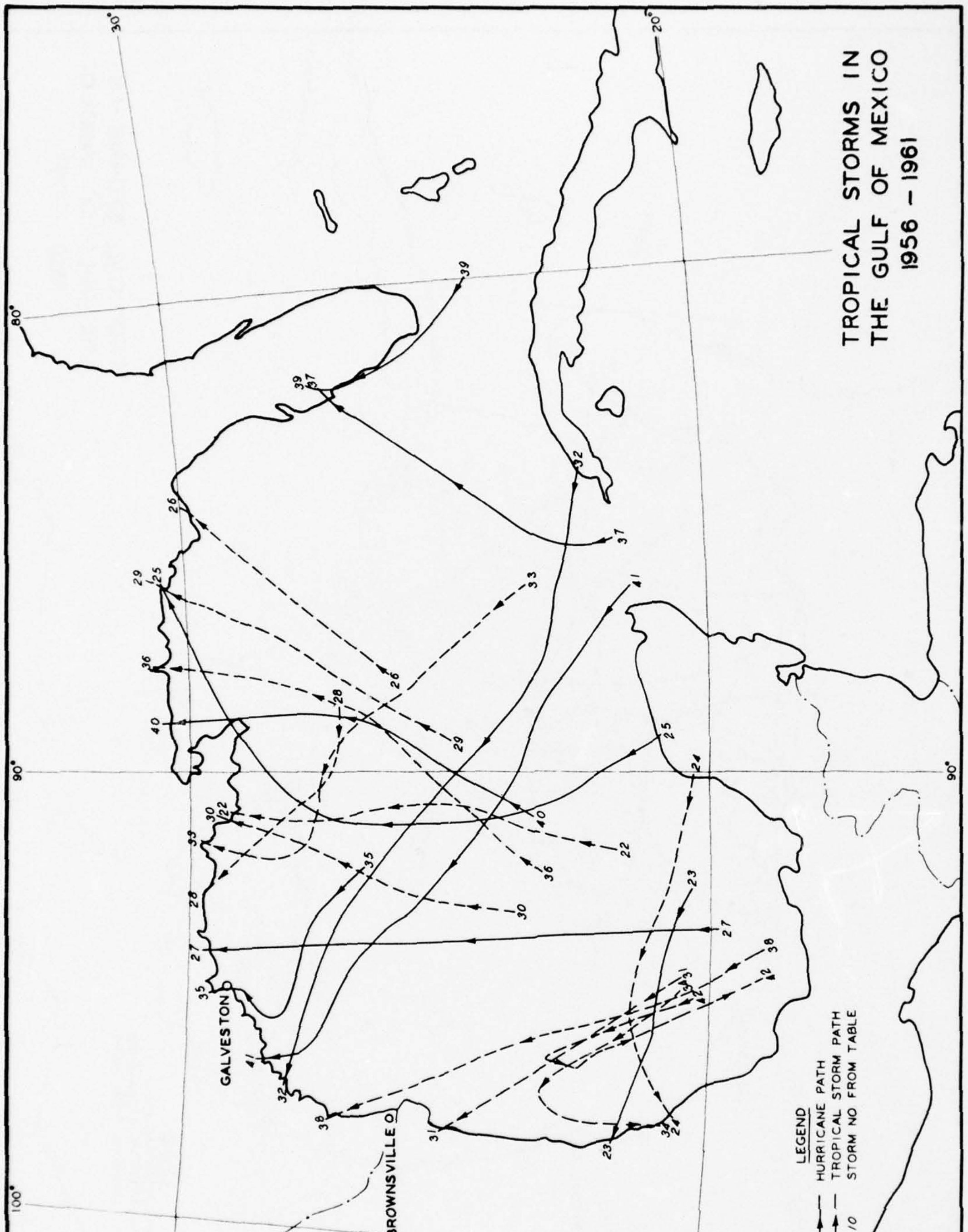
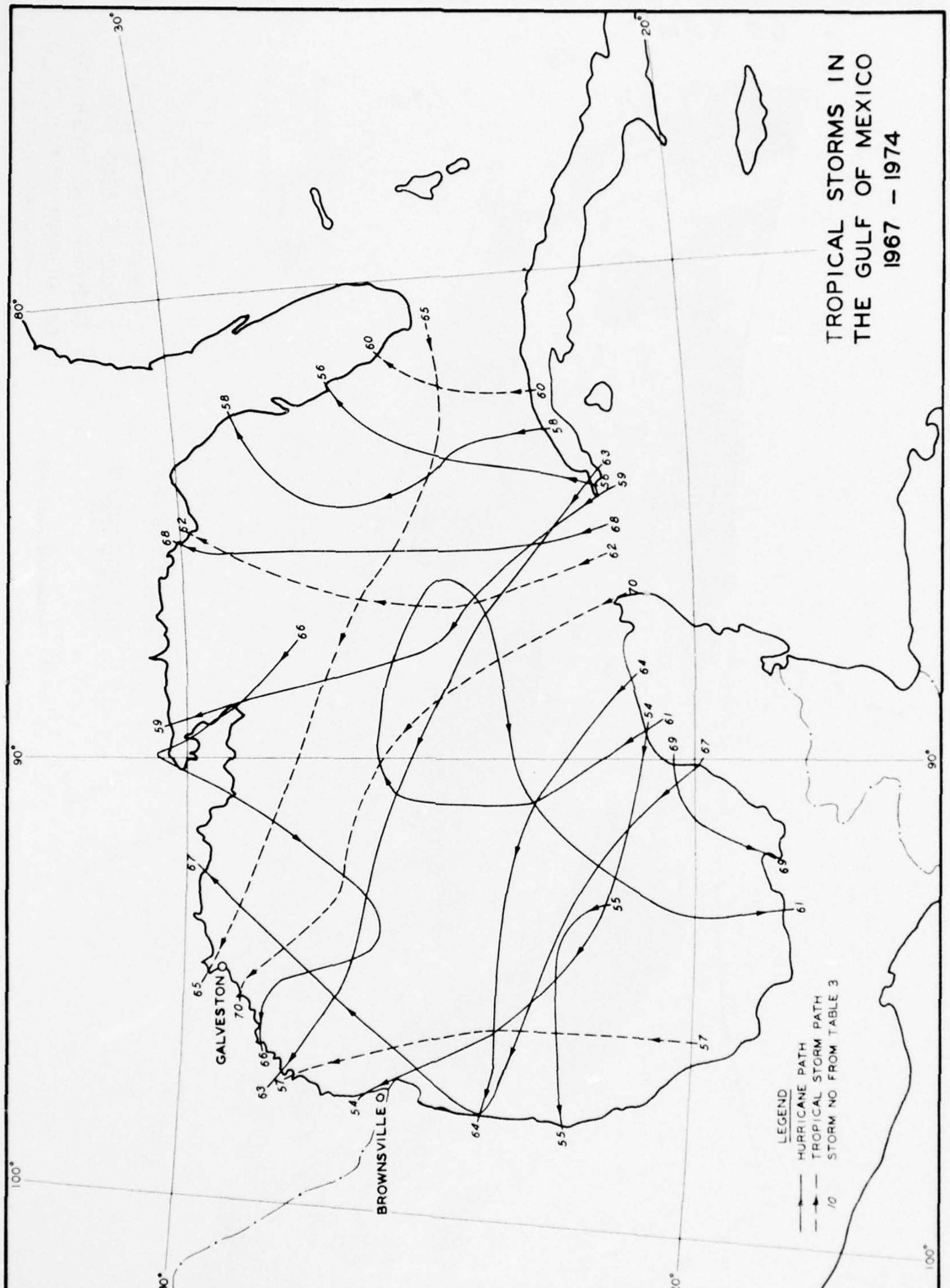
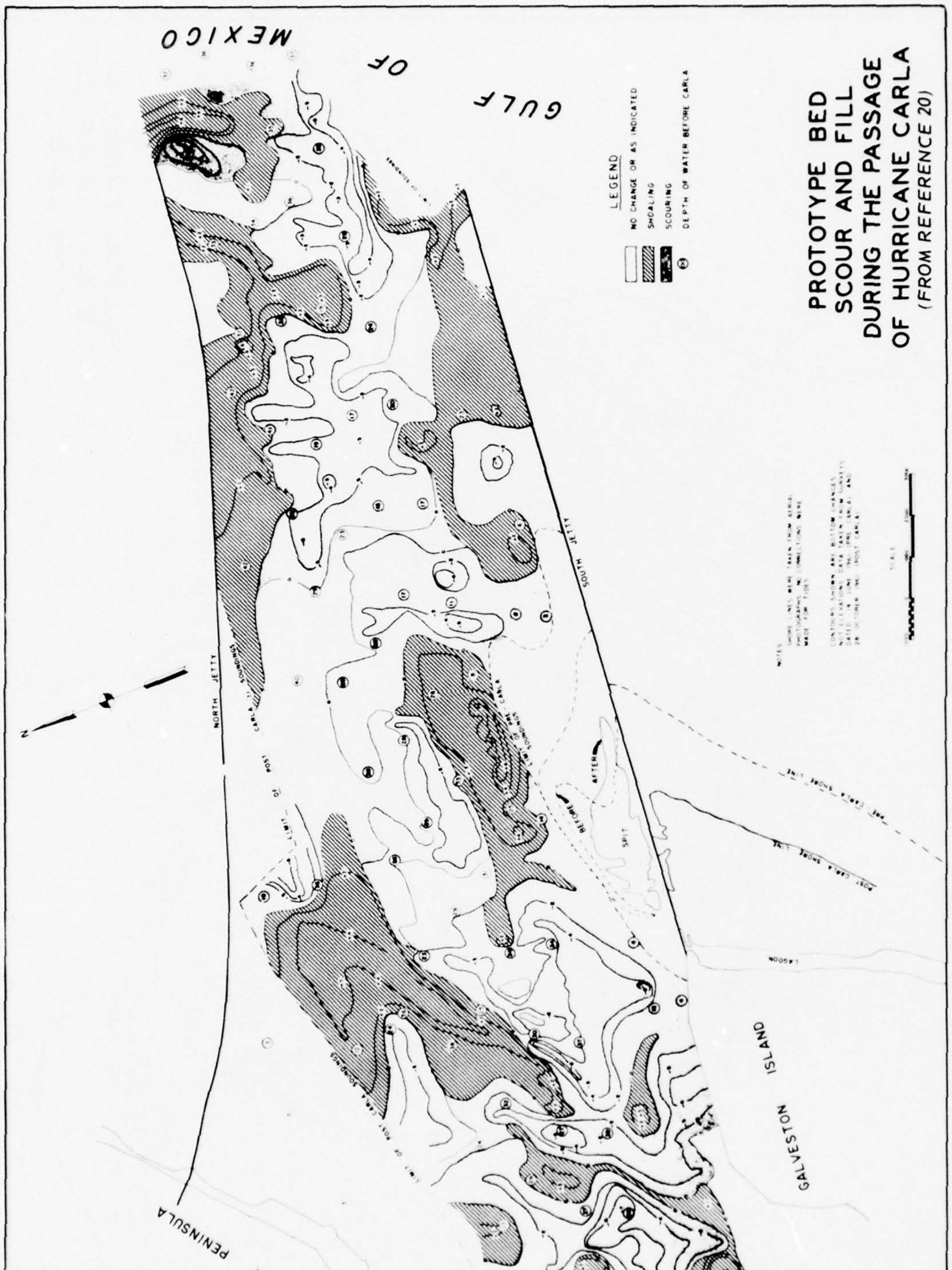

TROPICAL STORMS IN
THE GULF OF MEXICO
1956 – 1961
LEGEND
HURRICANE PATH
TROPICAL STORM PATH
10 STORM NO FROM TABLE
GALVESTON
BROWNSVILLE
30°
20°
80°
90°
100°

PLATE 4



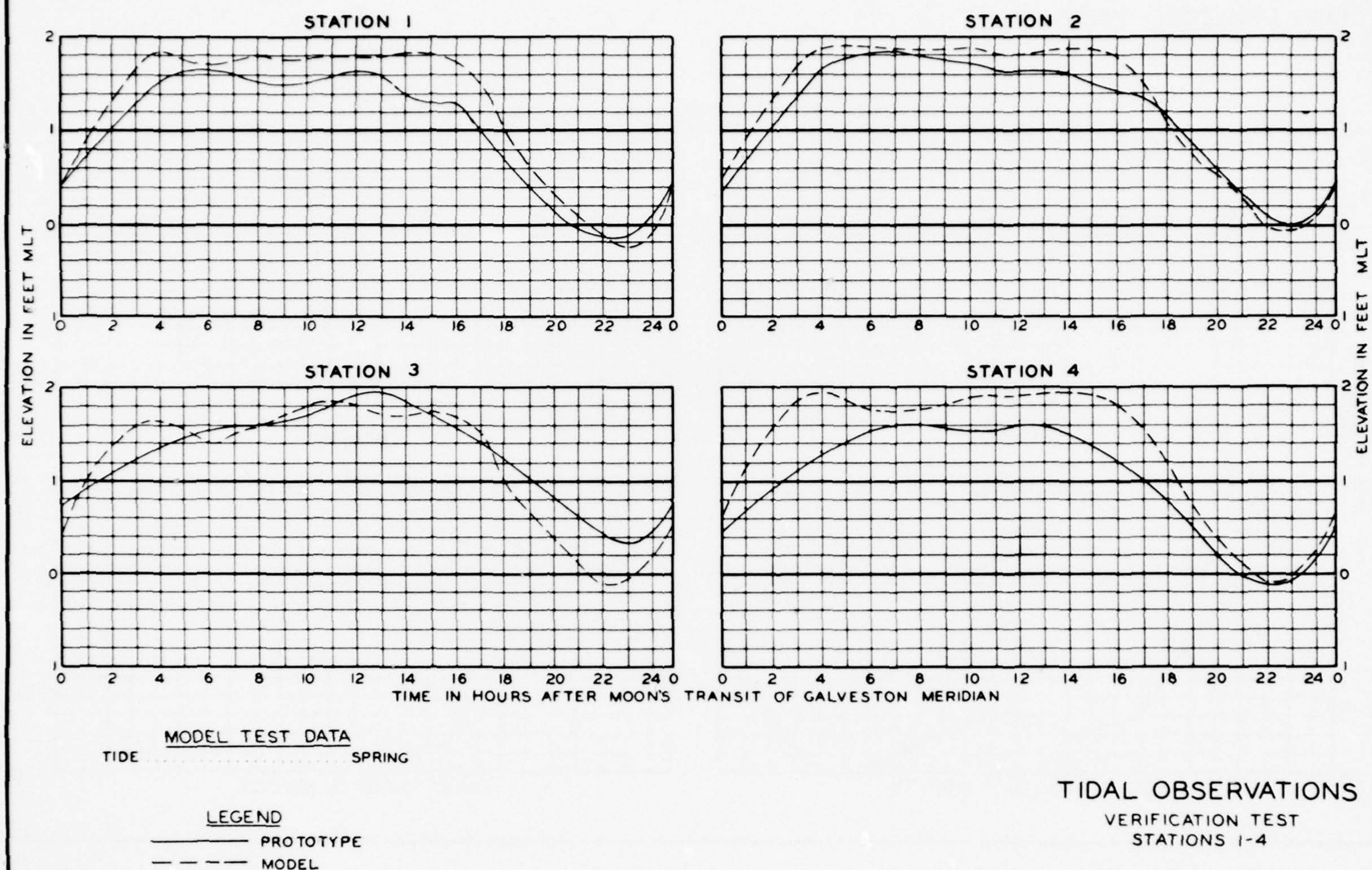
TROPICAL STORMS IN
THE GULF OF MEXICO
1967 – 1974
LEGEND
HURRICANE PATH
TROPICAL STORM PATH
STORM NO FROM TABLE 3
GALVESTON
BROWNSVILLE

PLATE 5

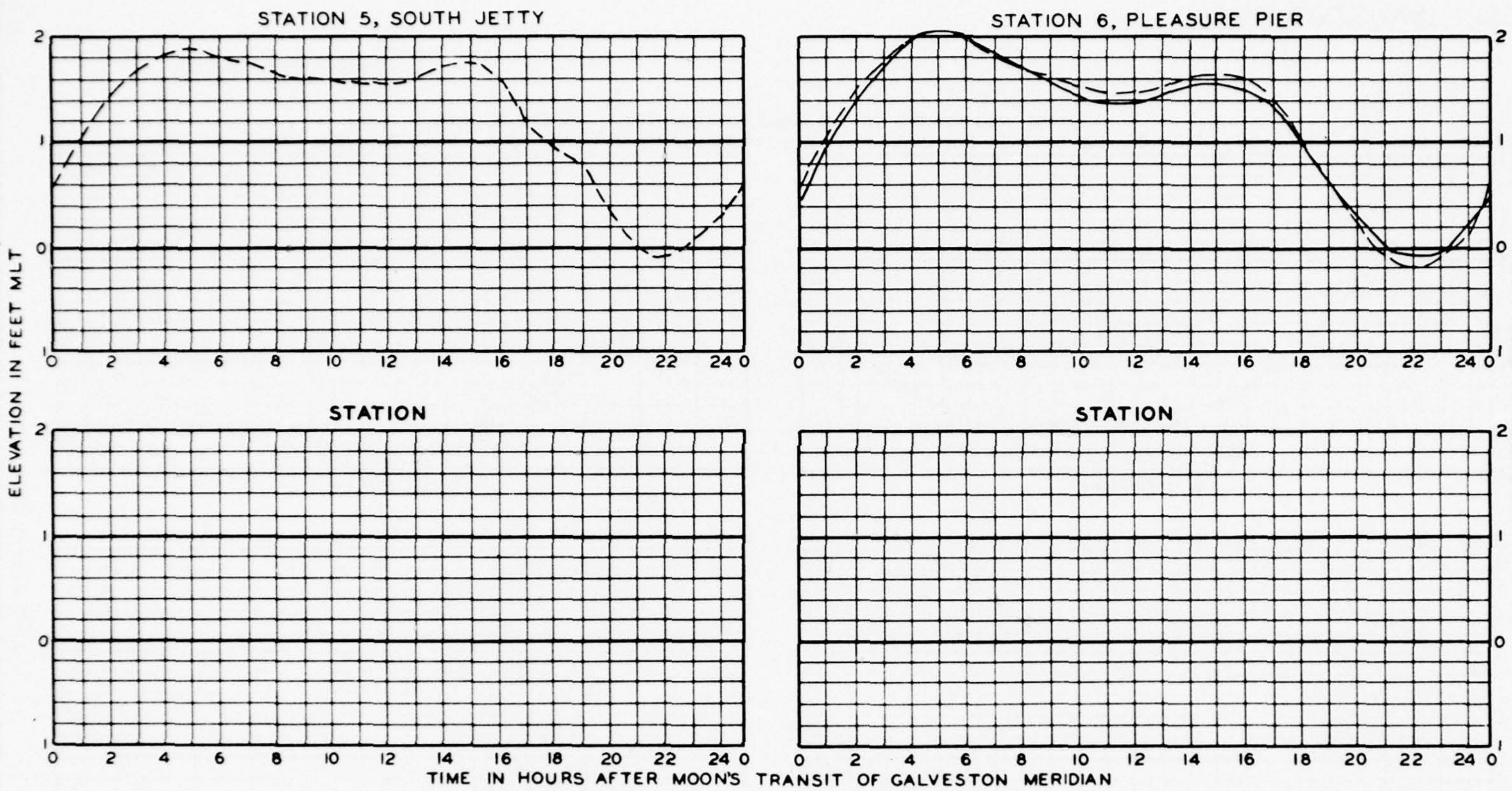


PROTOTYPE BED SCOUR AND FILL DURING THE PASSAGE OF HURRICANE CARLA
(FROM REFERENCE 20)

PLATE 6



TIDAL OBSERVATIONS
VERIFICATION TEST
STATIONS 1-4



MODEL TEST DATA

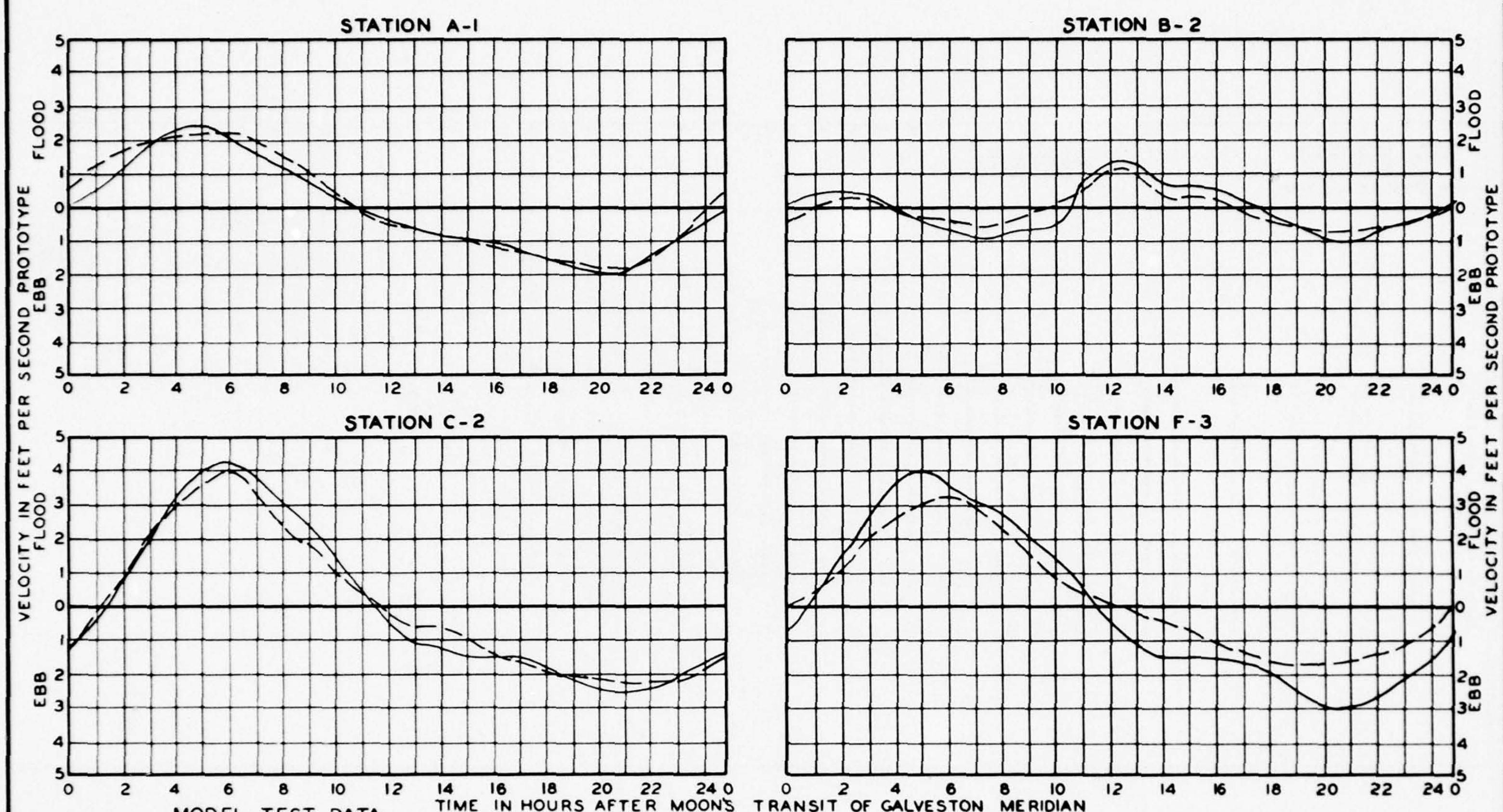
TIDE .... SPRING

LEGEND

———— PROTOTYPE
– – – – MODEL

TIDAL OBSERVATIONS

VERIFICATION TEST
STATIONS 5 AND 6



MODEL TEST DATA

TIDE .... SPRING

LEGEND

——— PROTOTYPE

– – – – MODEL

VELOCITY OBSERVATIONS

VERIFICATION TEST

PLATE 9

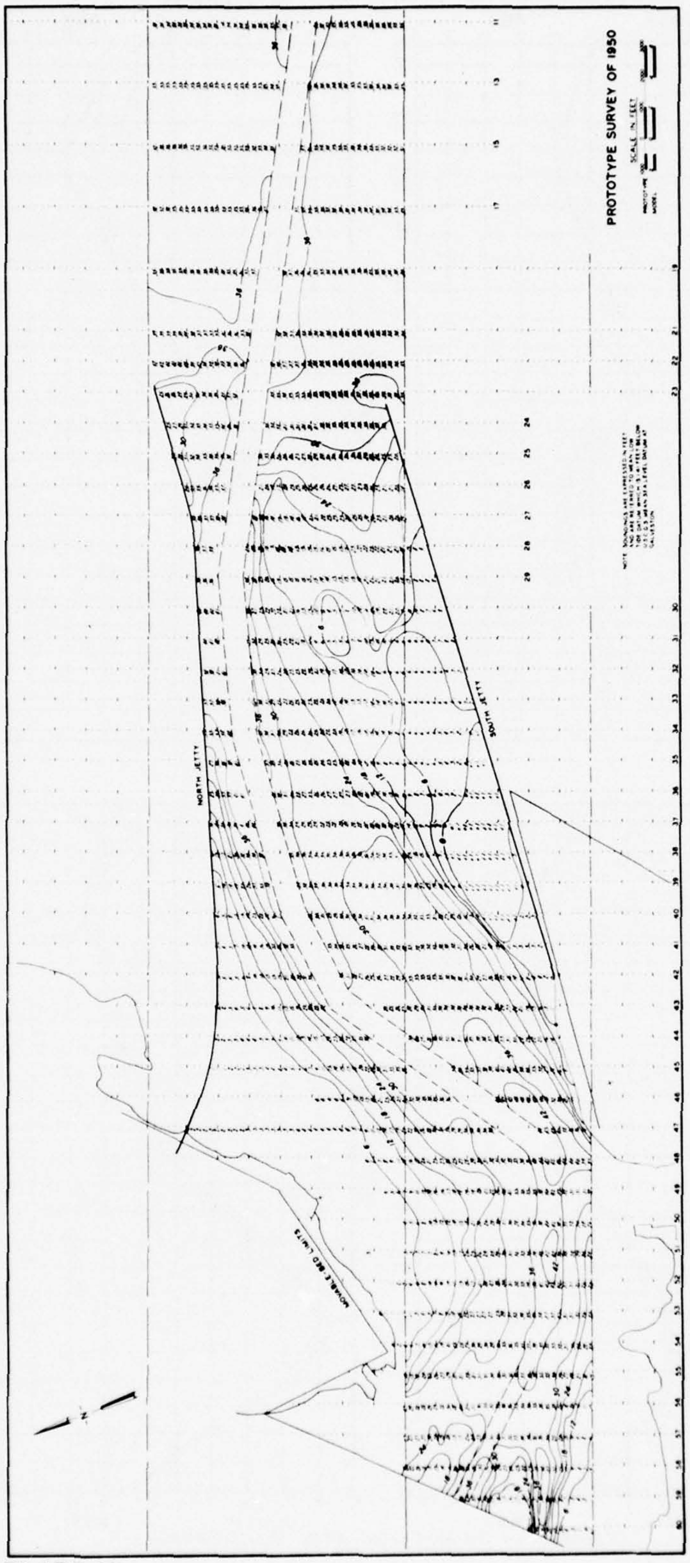

PROTOTYPE SURVEY OF 1950
NORTH JETTY
SOUTH JETTY
MOVABLE BED LIMITS

PLATE 10

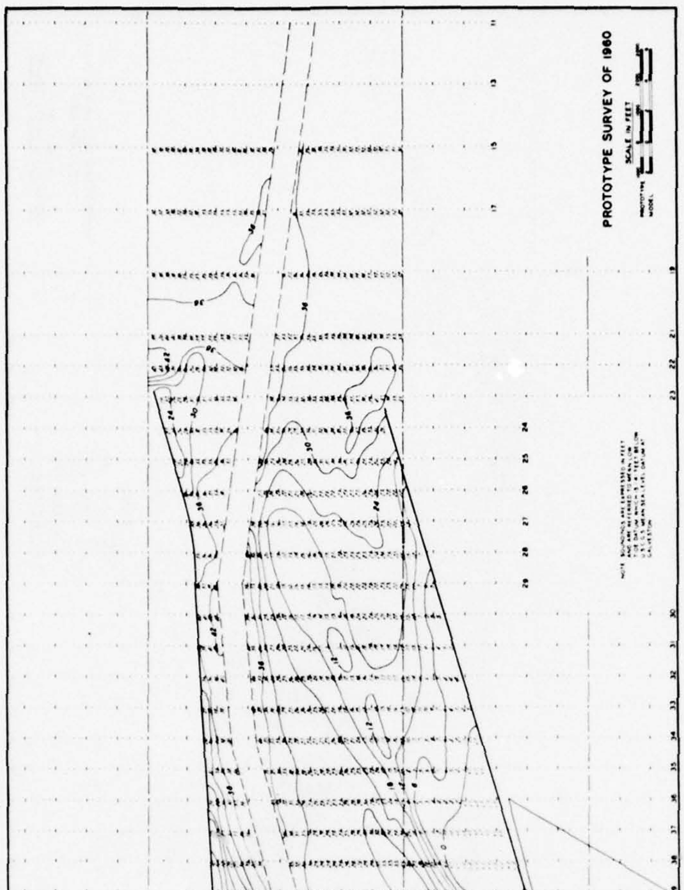


PLATE 11

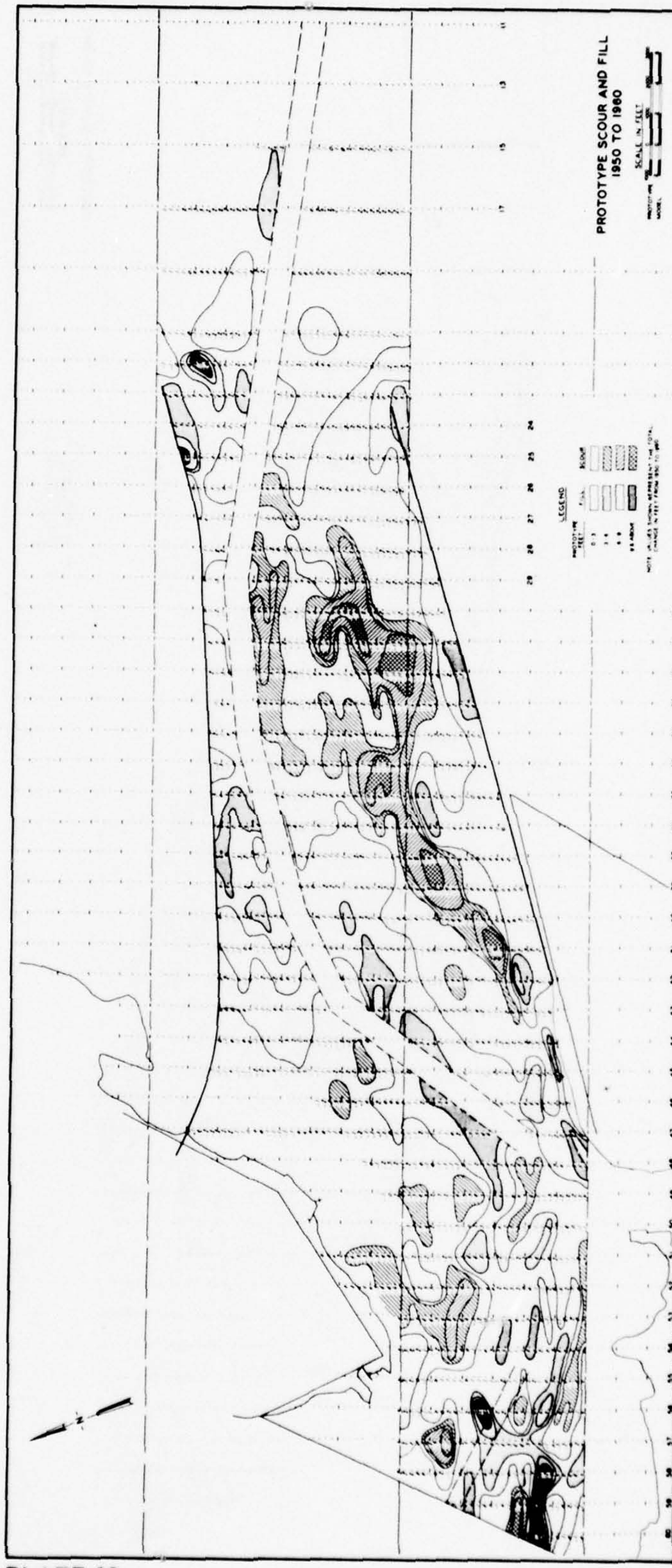

PROTOTYPE SCOUR AND FILL
1950 TO 1980
SCALE IN FEET
LEGEND
FILL
SCOUR

PLATE 12

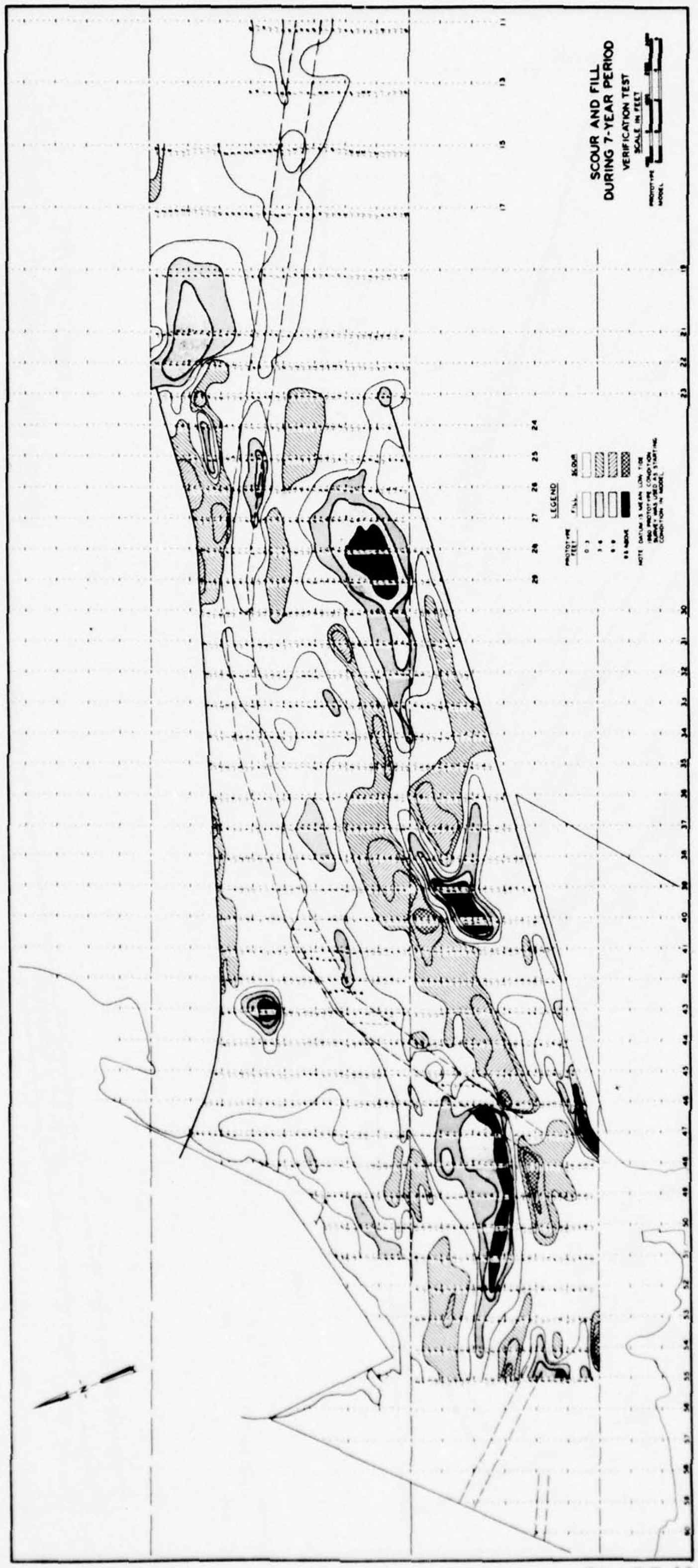
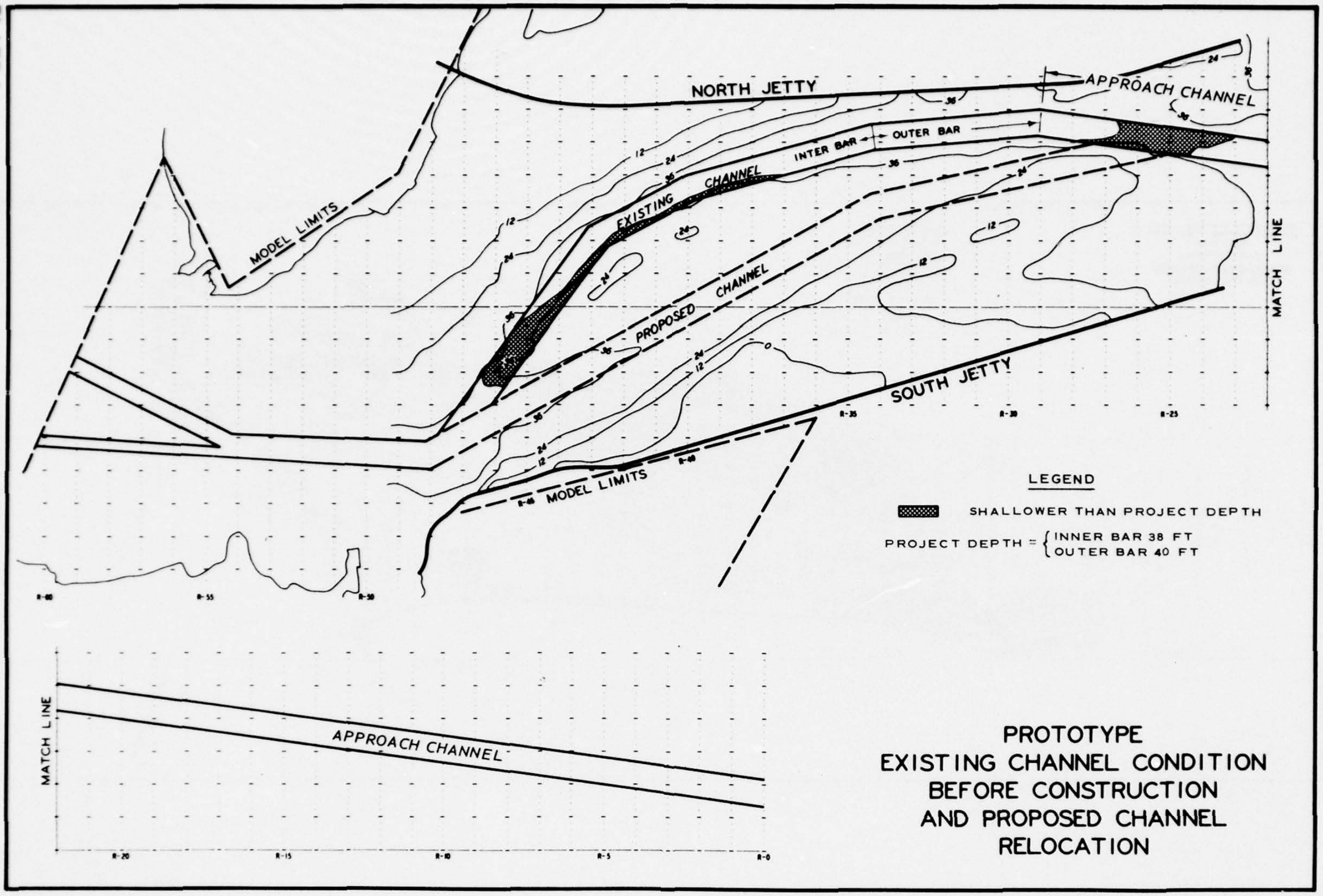
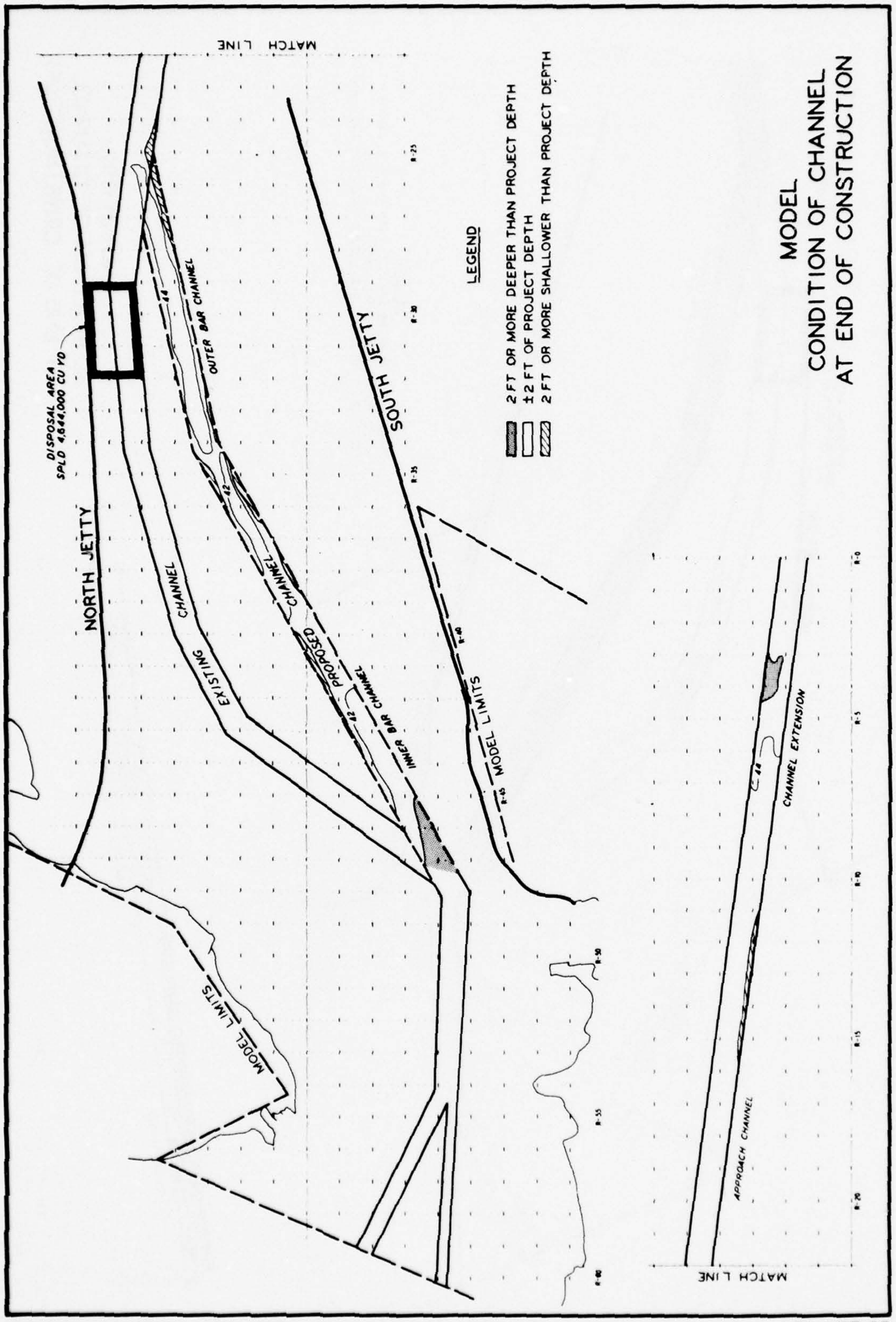

SCOUR AND FILL
DURING 7-YEAR PERIOD
VERIFICATION TEST
SCALE IN FEET
PROTOTYPE
MODEL
LEGEND

PLATE 13



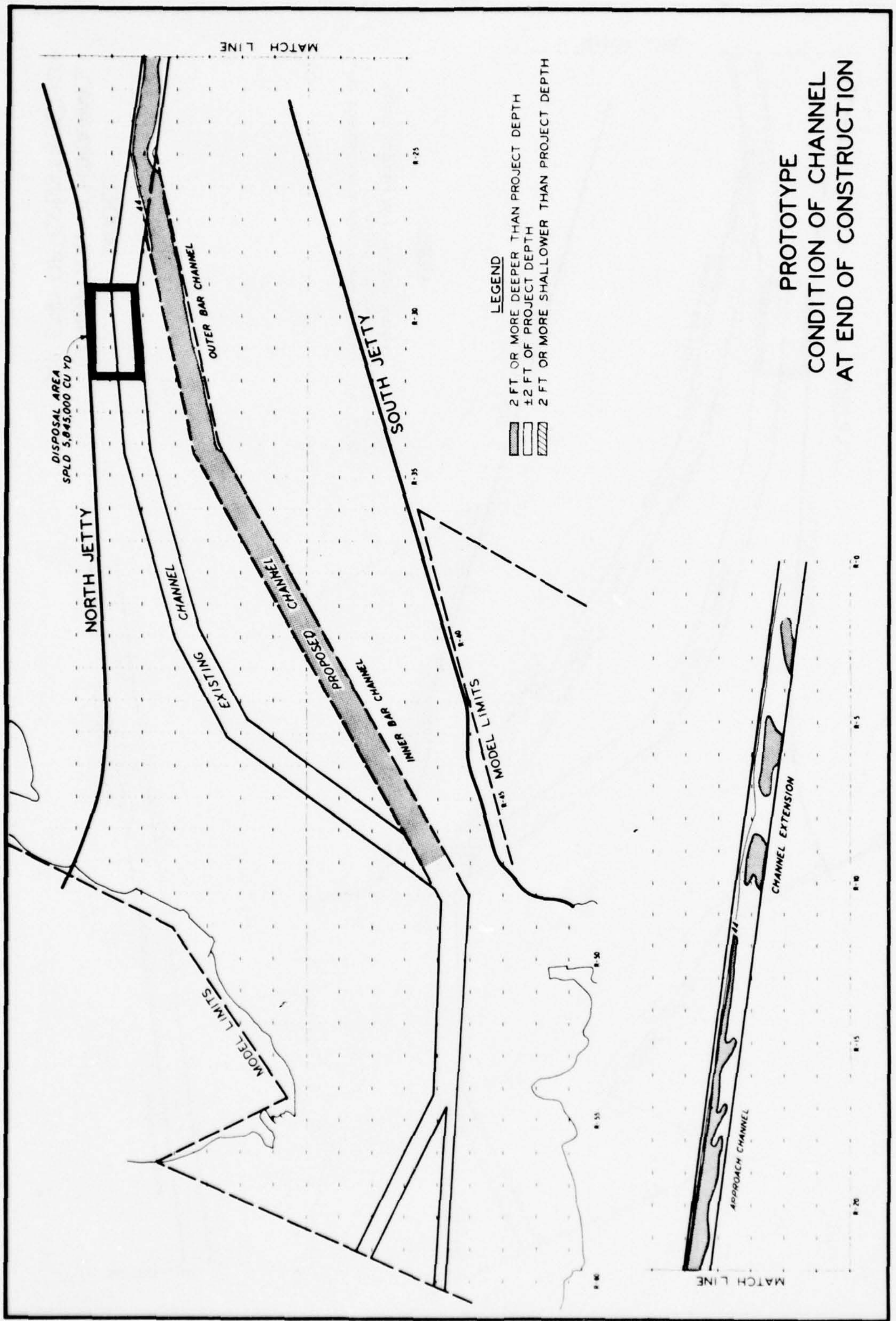
PROTOTYPE
EXISTING CHANNEL CONDITION
BEFORE CONSTRUCTION
AND PROPOSED CHANNEL
RELOCATION

PLATE 14

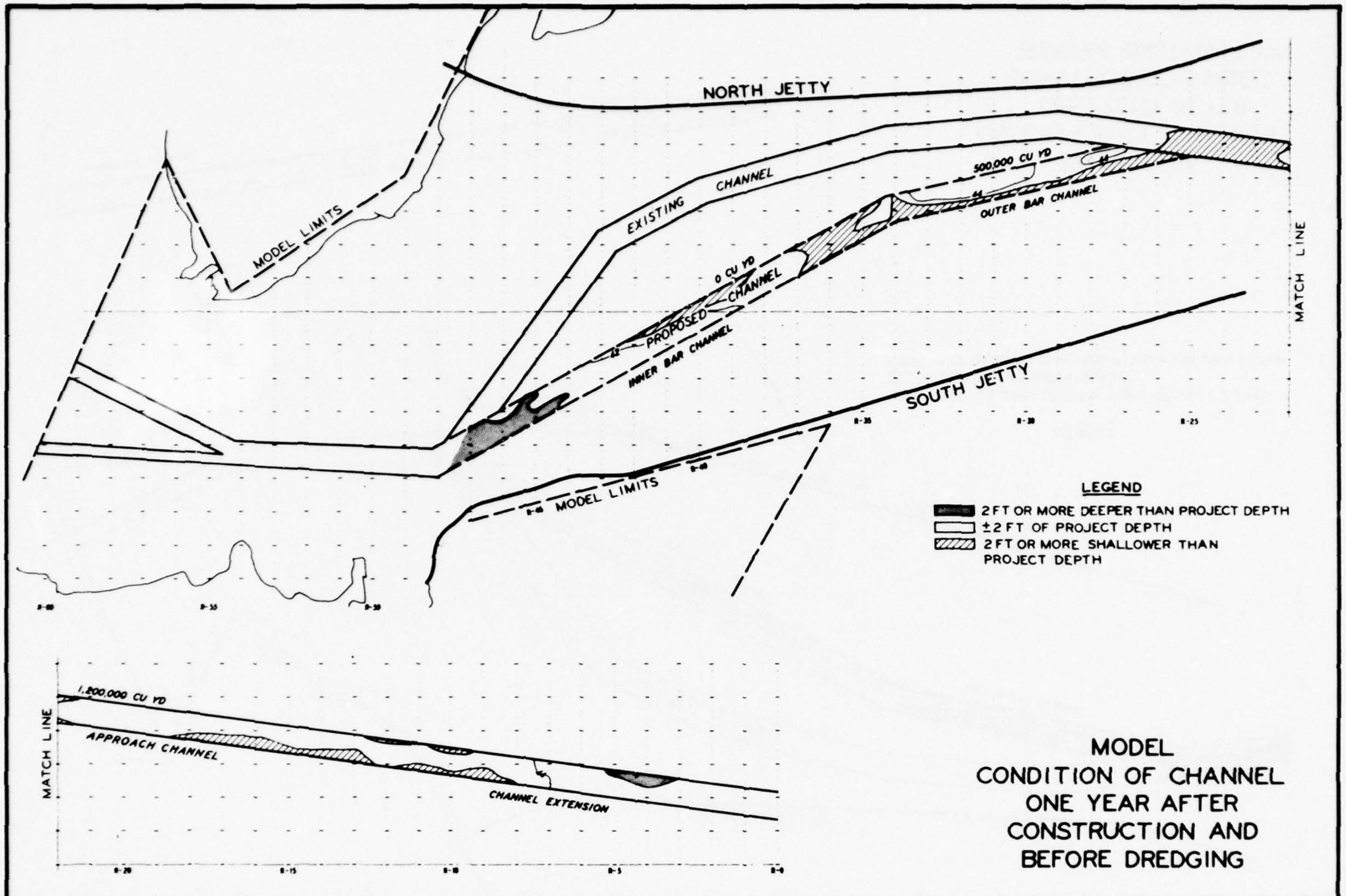


MODEL
CONDITION OF CHANNEL
AT END OF CONSTRUCTION

PLATE 15



PROTOTYPE
CONDITION OF CHANNEL
AT END OF CONSTRUCTION
LEGEND
2 FT OR MORE DEEPER THAN PROJECT DEPTH
±2 FT OF PROJECT DEPTH
2 FT OR MORE SHALLOWER THAN PROJECT DEPTH
NORTH JETTY
SOUTH JETTY
DISPOSAL AREA
SPLD 5,845,000 CU YD
EXISTING CHANNEL
PROPOSED CHANNEL
INNER BAR CHANNEL
OUTER BAR CHANNEL
MODEL LIMITS
MODEL LIMITS
CHANNEL EXTENSION
APPROACH CHANNEL
MATCH LINE
MATCH LINE



MODEL
CONDITION OF CHANNEL
ONE YEAR AFTER
CONSTRUCTION AND
BEFORE DREDGING

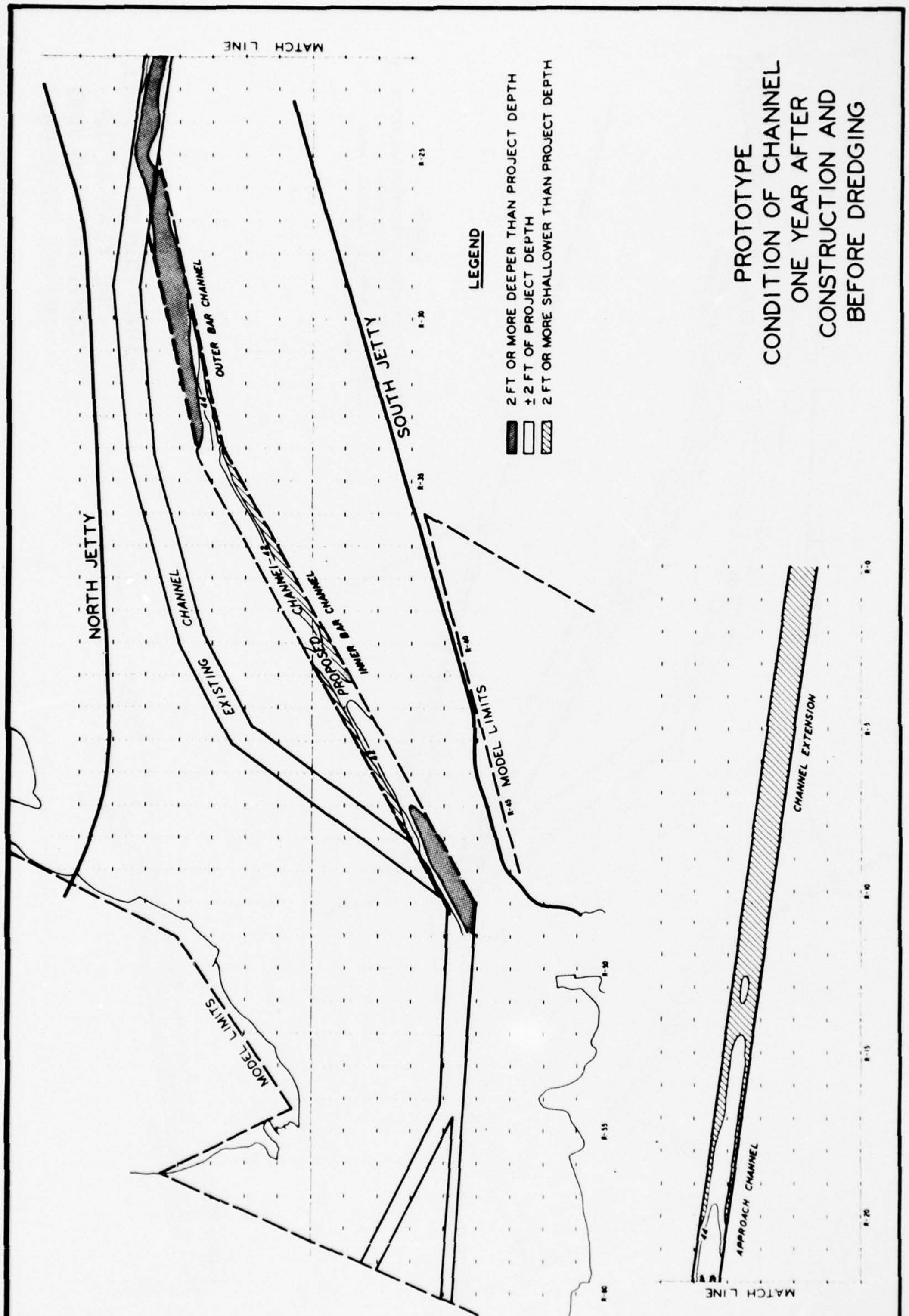
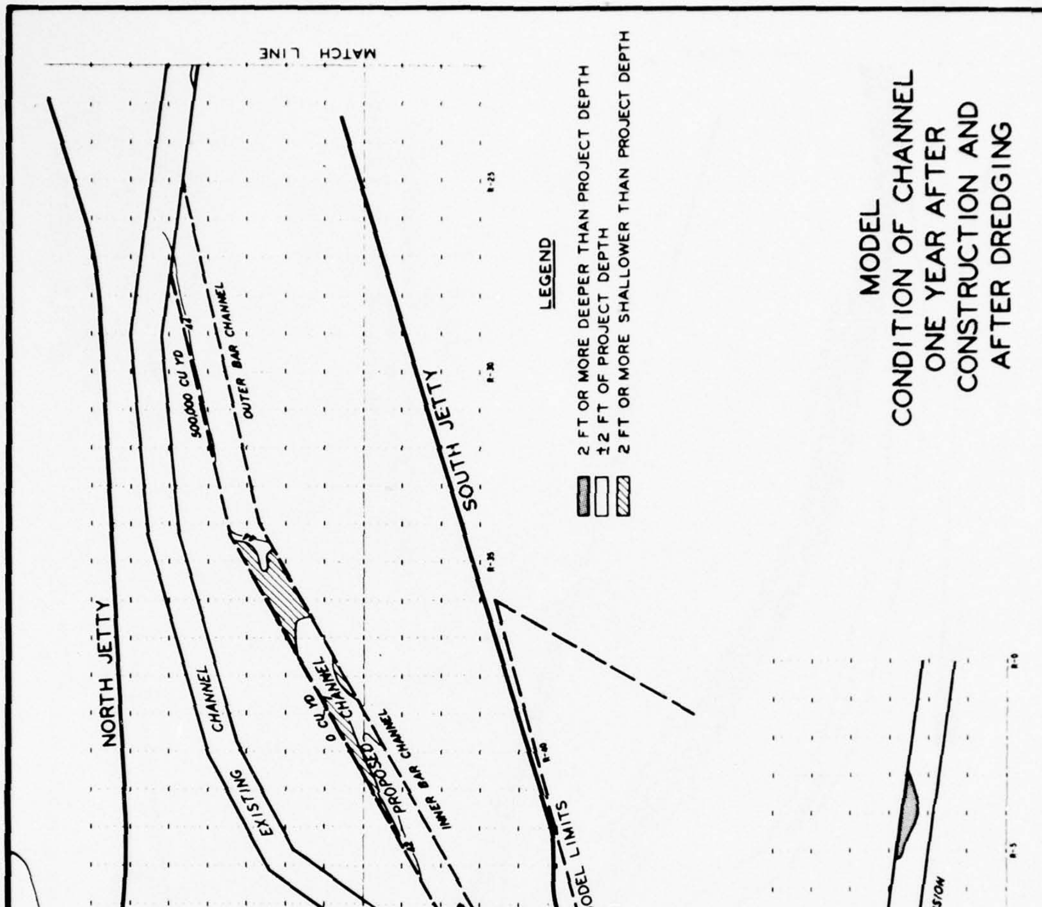
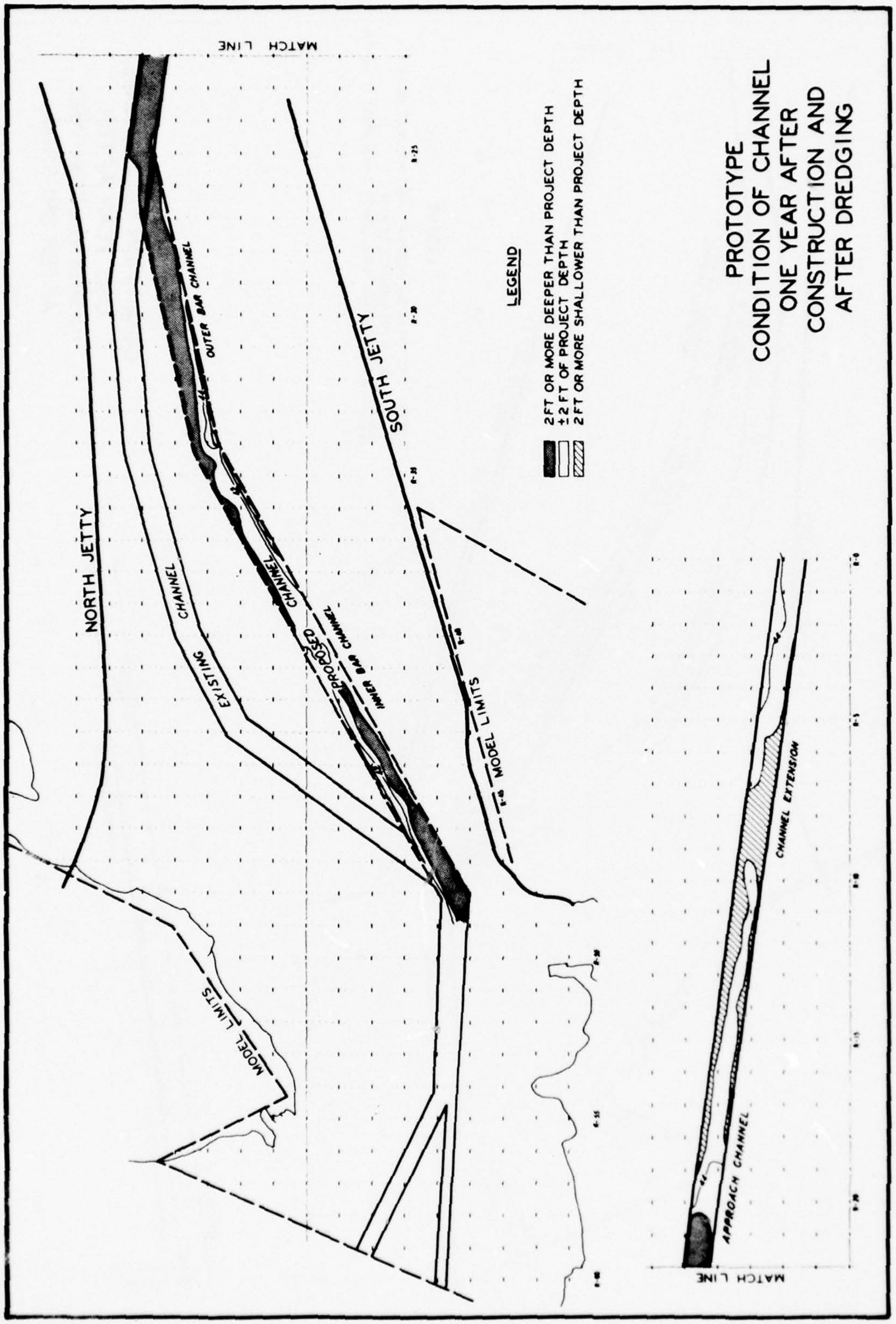

PROTOTYPE
CONDITION OF CHANNEL
ONE YEAR AFTER
CONSTRUCTION AND
BEFORE DREDGING
LEGEND
2 FT OR MORE DEEPER THAN PROJECT DEPTH
± 2 FT OF PROJECT DEPTH
2 FT OR MORE SHALLOWER THAN PROJECT DEPTH
NORTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
INNER BAR CHANNEL
OUTER BAR CHANNEL
SOUTH JETTY
MODEL LIMITS
MODEL LIMITS
CHANNEL EXTENSION
APPROACH CHANNEL
MATCH LINE
MATCH LINE

PLATE 18

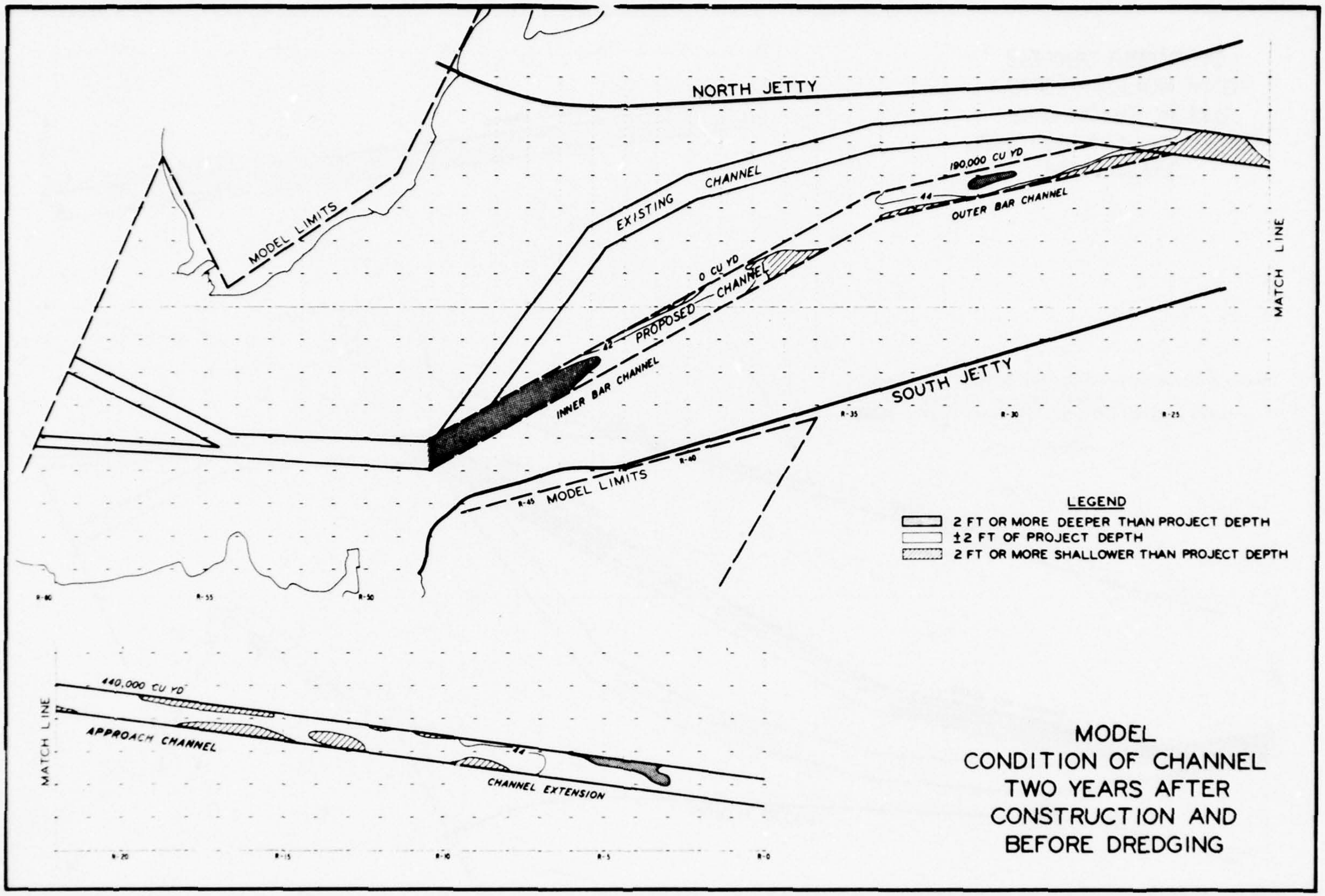


MODEL
CONDITION OF CHANNEL
ONE YEAR AFTER
CONSTRUCTION AND
AFTER DREDGING

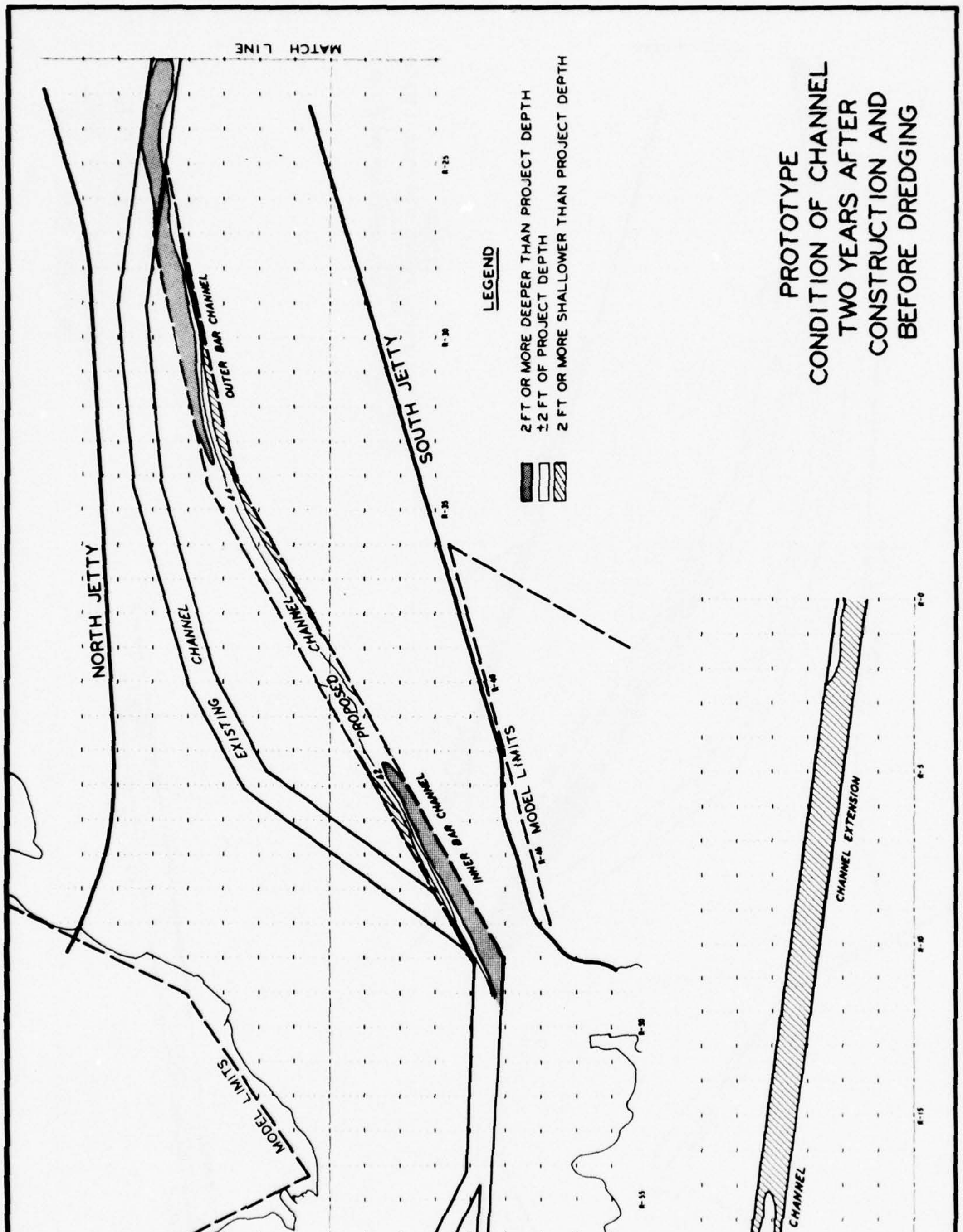


PROTOTYPE
CONDITION OF CHANNEL
ONE YEAR AFTER
CONSTRUCTION AND
AFTER DREDGING

PLATE 20

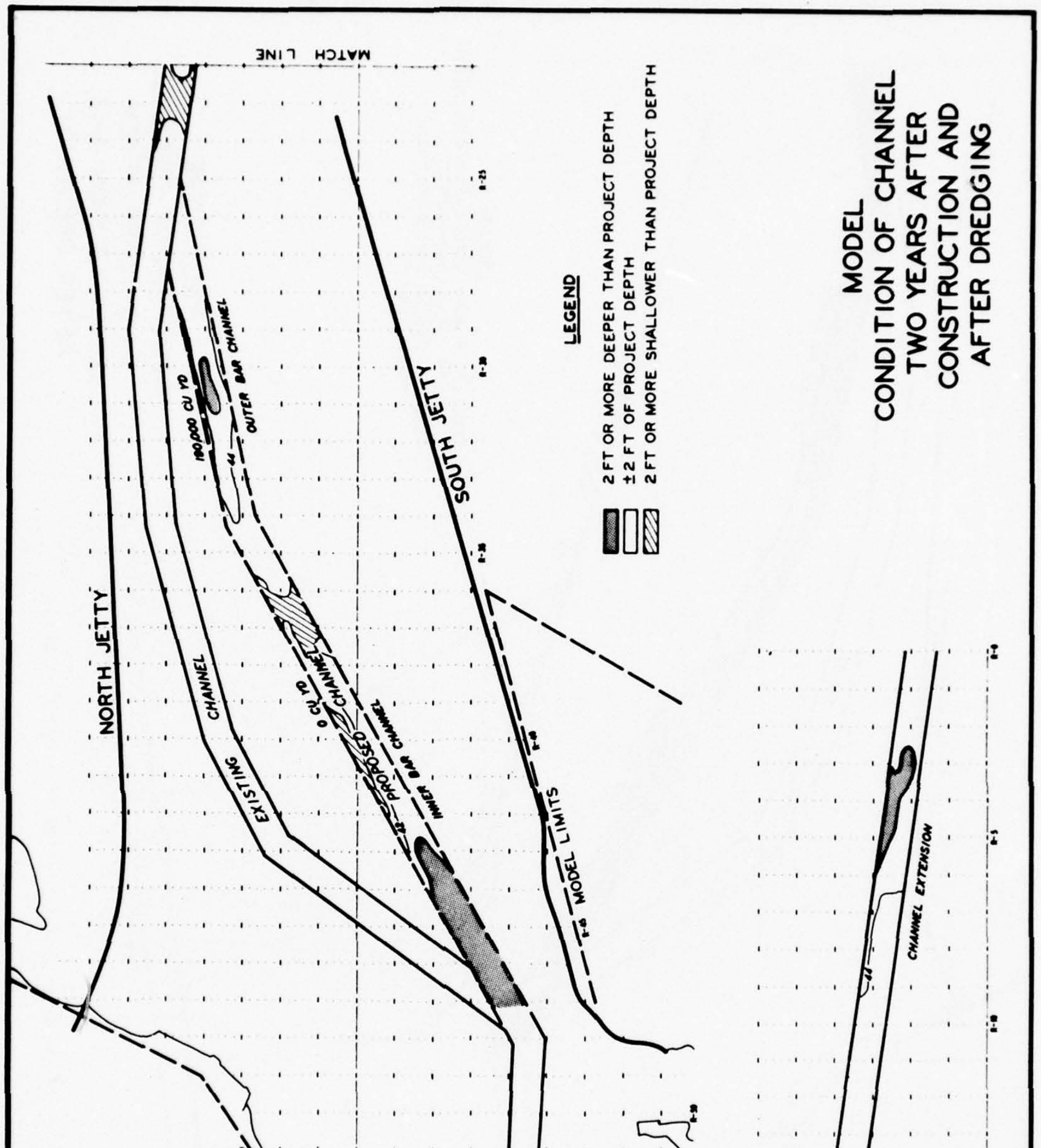


MODEL
CONDITION OF CHANNEL
TWO YEARS AFTER
CONSTRUCTION AND
BEFORE DREDGING



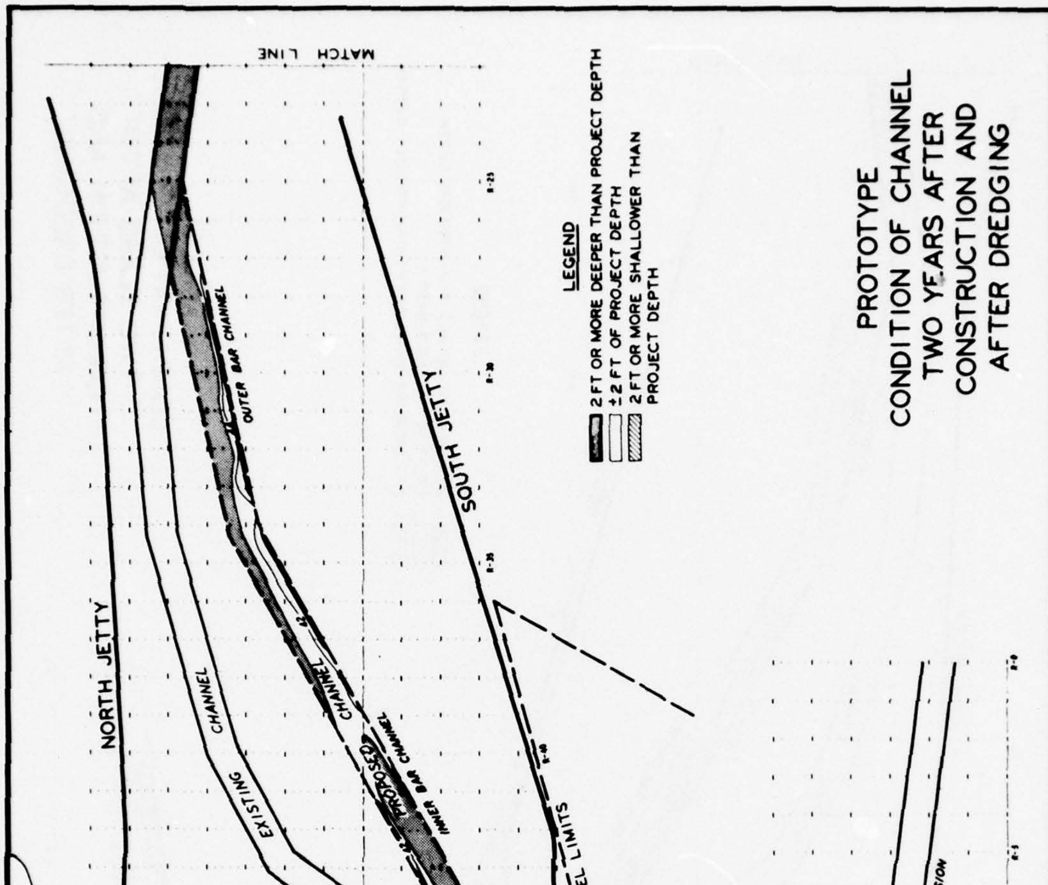
PROTOTYPE
CONDITION OF CHANNEL
TWO YEARS AFTER
CONSTRUCTION AND
BEFORE DREDGING

PLATE 22



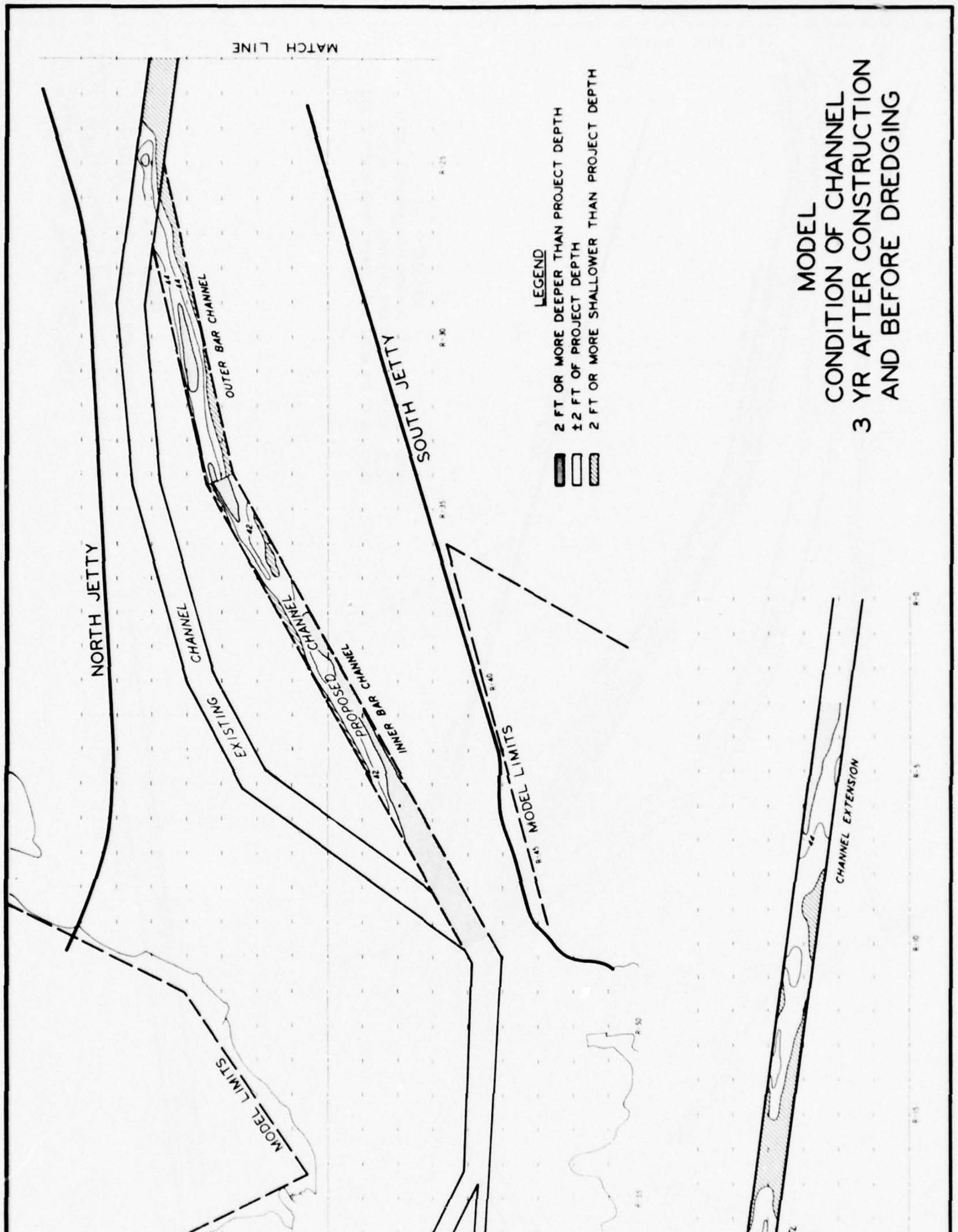
MODEL
CONDITION OF CHANNEL
TWO YEARS AFTER
CONSTRUCTION AND
AFTER DREDGING

PLATE 23

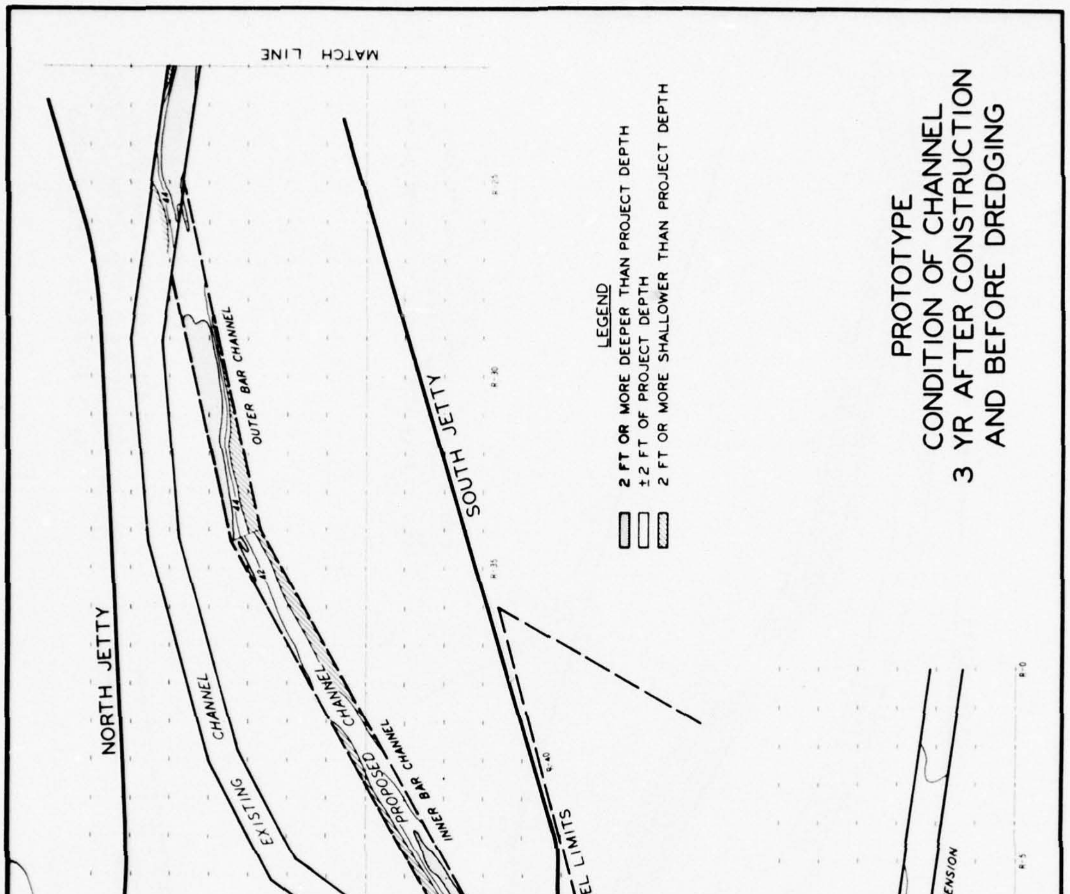


PROTOTYPE
CONDITION OF CHANNEL
TWO YEARS AFTER
CONSTRUCTION AND
AFTER DREDGING

PLATE 24

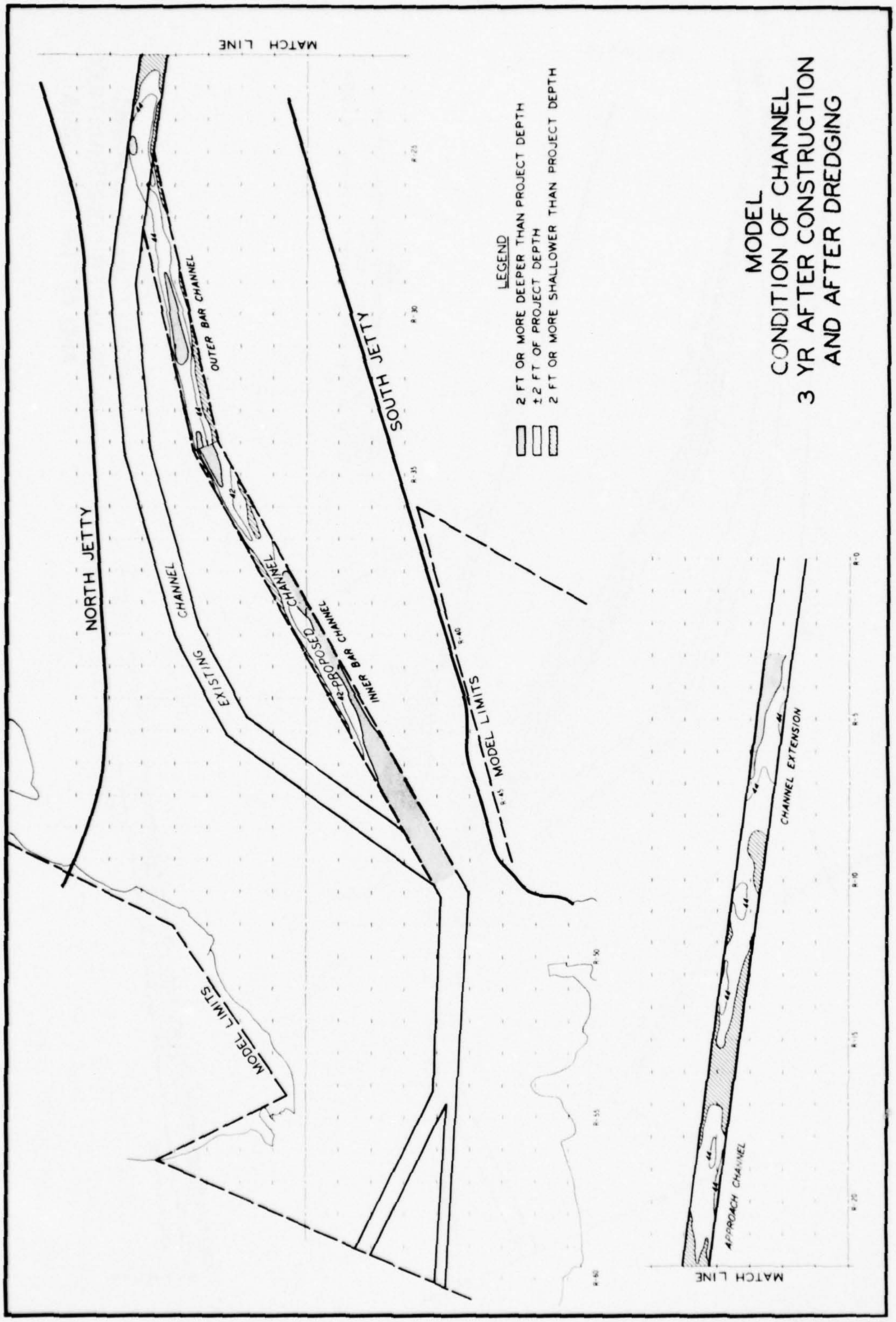


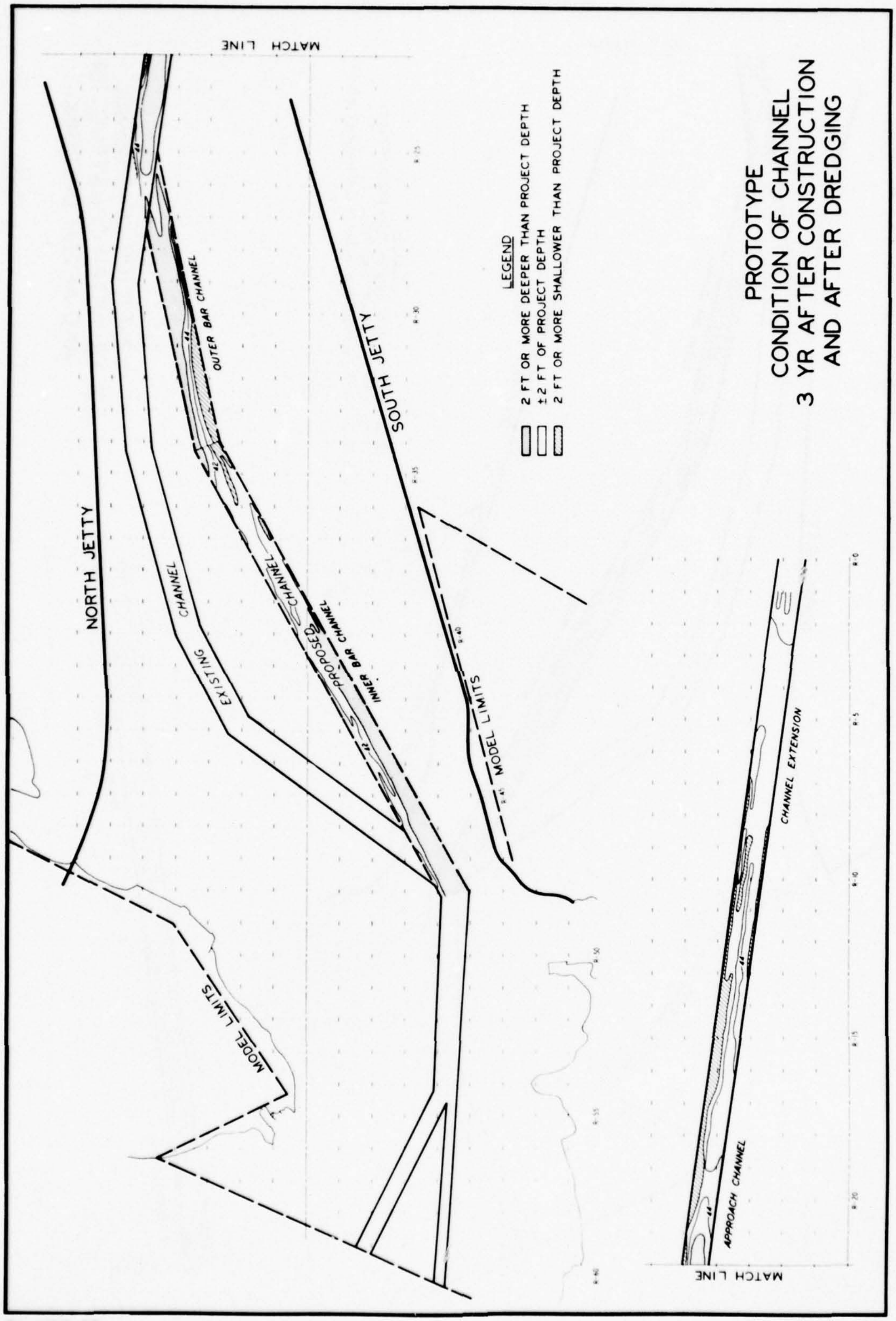
MODEL
CONDITION OF CHANNEL
3 YR AFTER CONSTRUCTION
AND BEFORE DREDGING



PROTOTYPE
CONDITION OF CHANNEL
3 YR AFTER CONSTRUCTION
AND BEFORE DREDGING

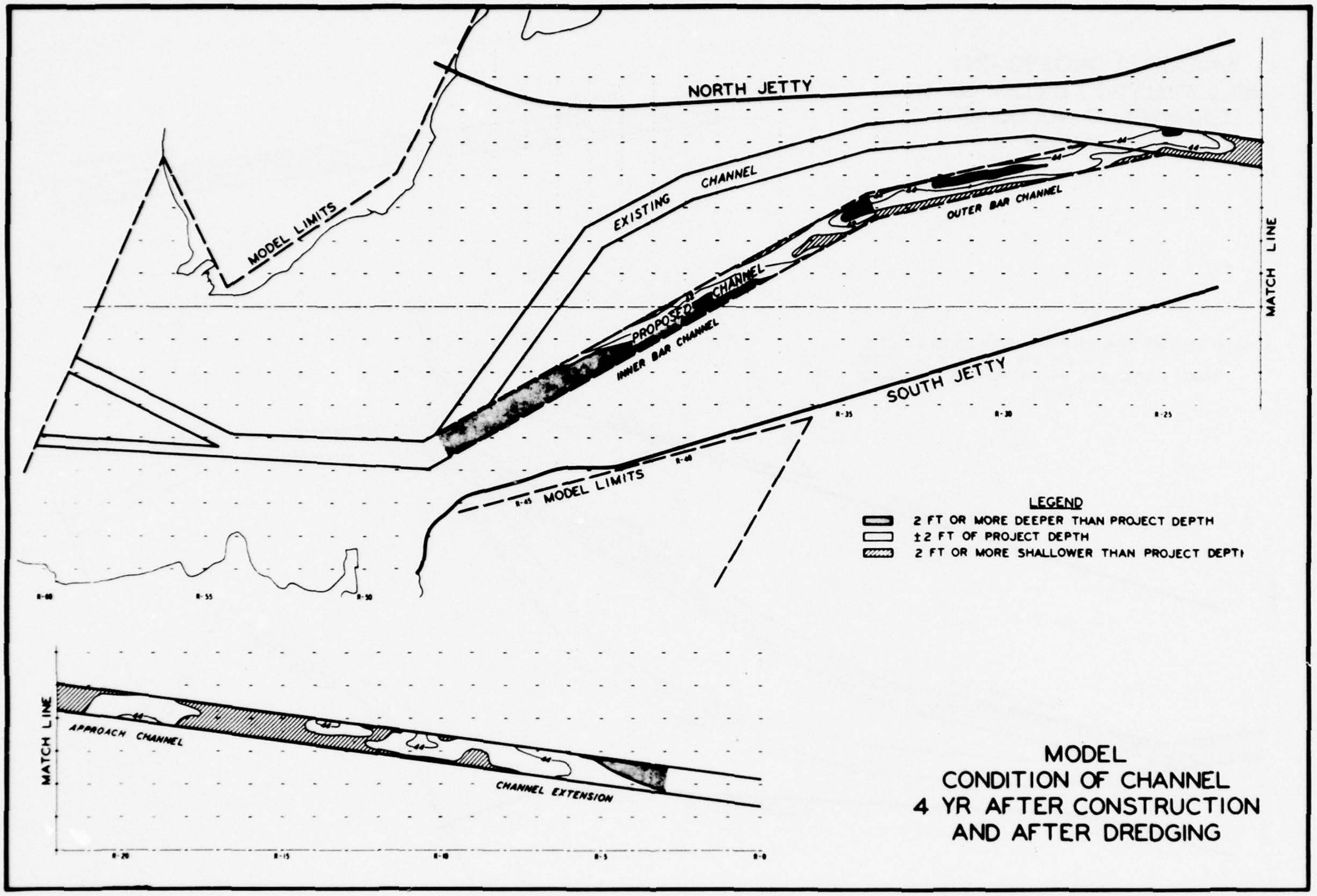
PLATE 26


MODEL
CONDITION OF CHANNEL
3 YR AFTER CONSTRUCTION
AND AFTER DREDGING
LEGEND
2 FT OR MORE DEEPER THAN PROJECT DEPTH
±2 FT OF PROJECT DEPTH
2 FT OR MORE SHALLOWER THAN PROJECT DEPTH
NORTH JETTY
SOUTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
OUTER BAR CHANNEL
INNER BAR CHANNEL
MODEL LIMITS
MODEL LIMITS
MATCH LINE
MATCH LINE
CHANNEL EXTENSION
APPROACH CHANNEL

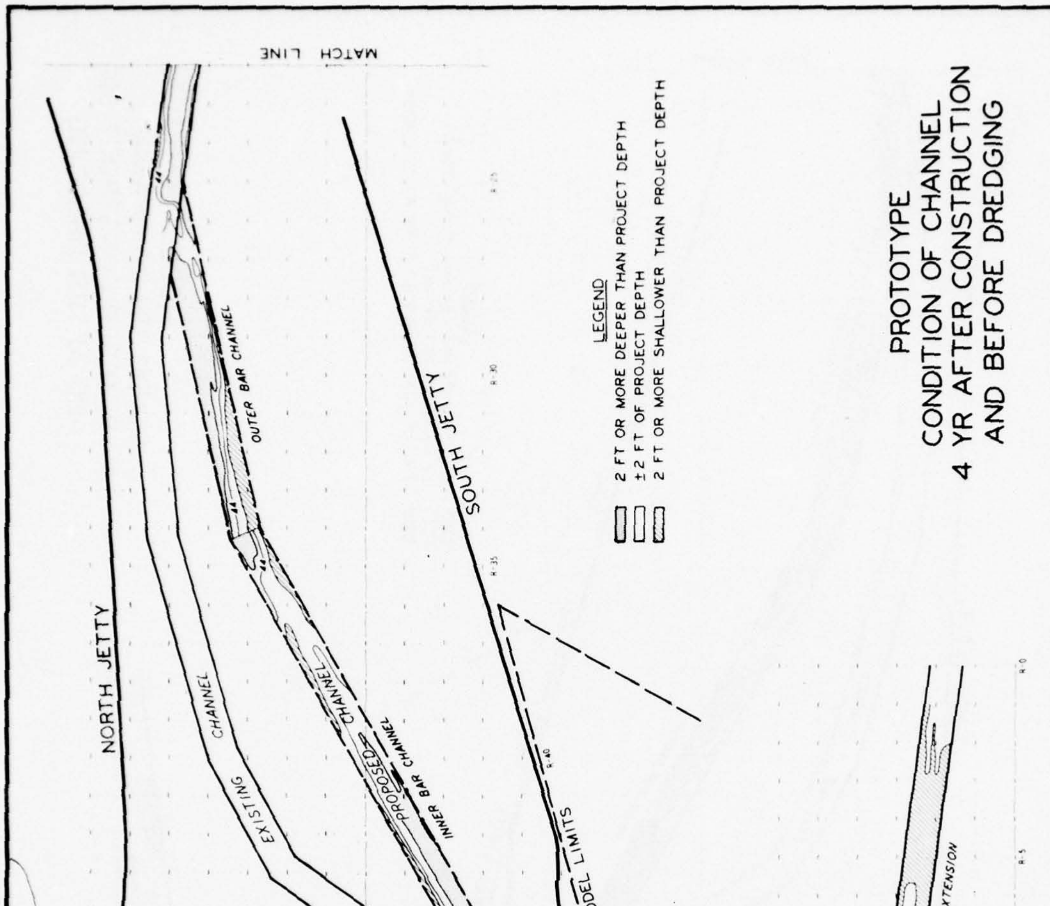


PROTOTYPE
CONDITION OF CHANNEL
3 YR AFTER CONSTRUCTION
AND AFTER DREDGING

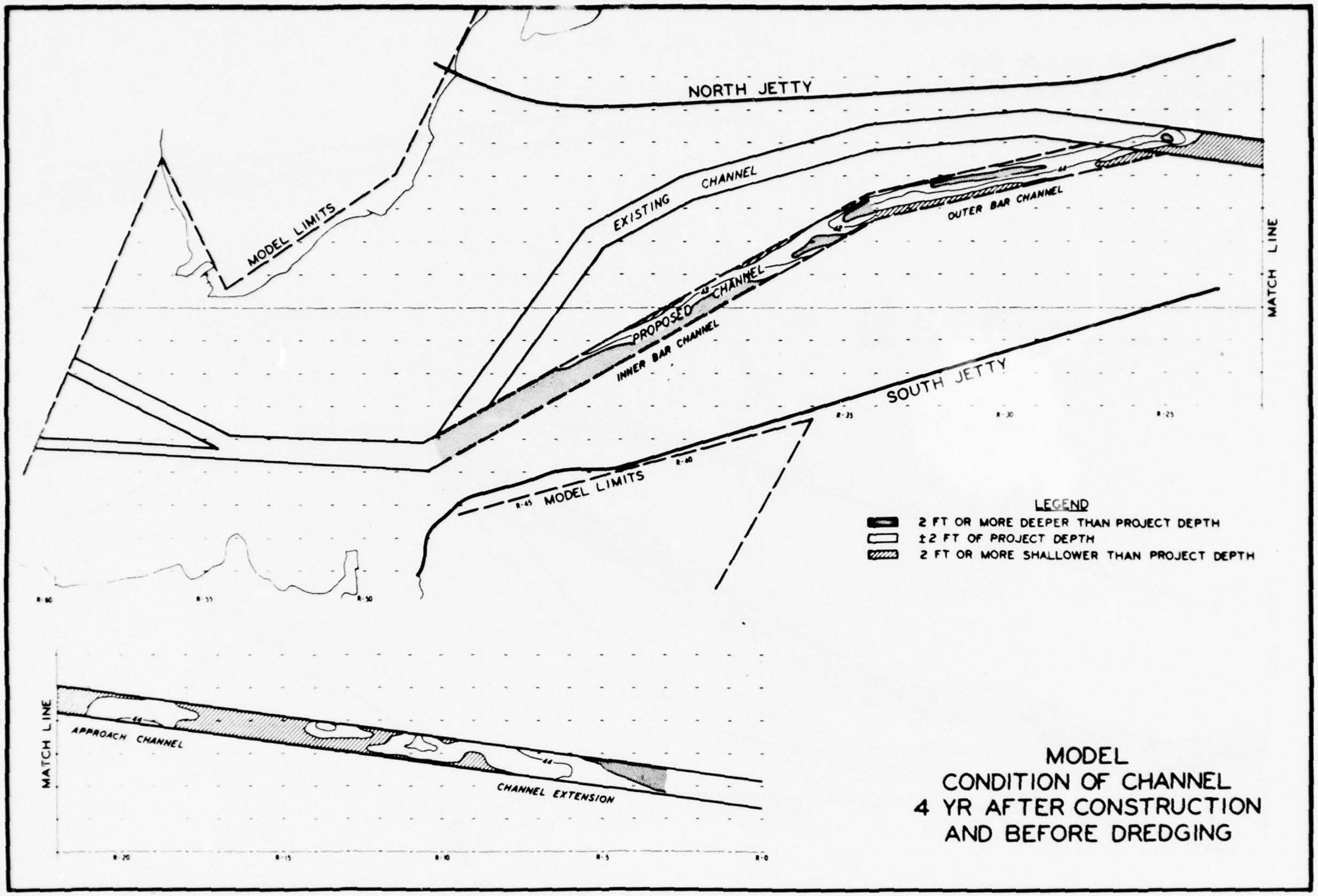
PLATE 28



MODEL
CONDITION OF CHANNEL
4 YR AFTER CONSTRUCTION
AND AFTER DREDGING



PROTOTYPE
CONDITION OF CHANNEL
4 YR AFTER CONSTRUCTION
AND BEFORE DREDGING



MODEL
CONDITION OF CHANNEL
4 YR AFTER CONSTRUCTION
AND BEFORE DREDGING

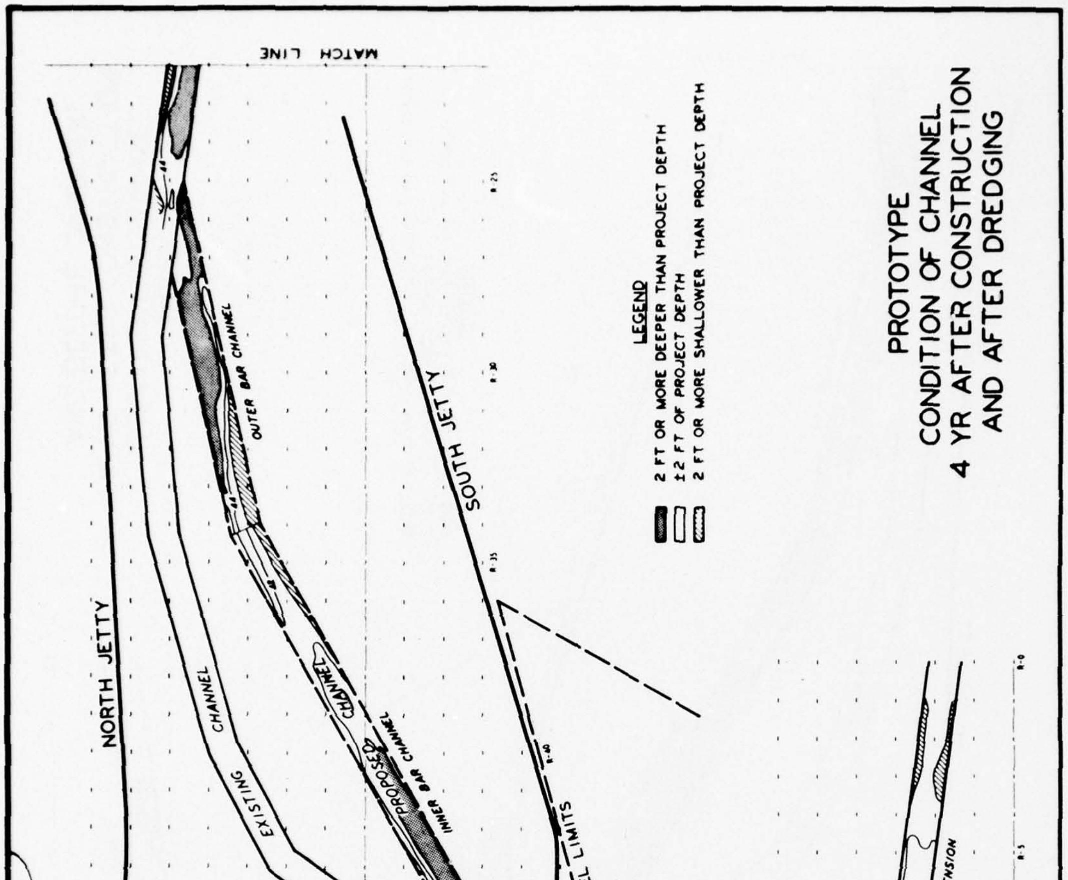
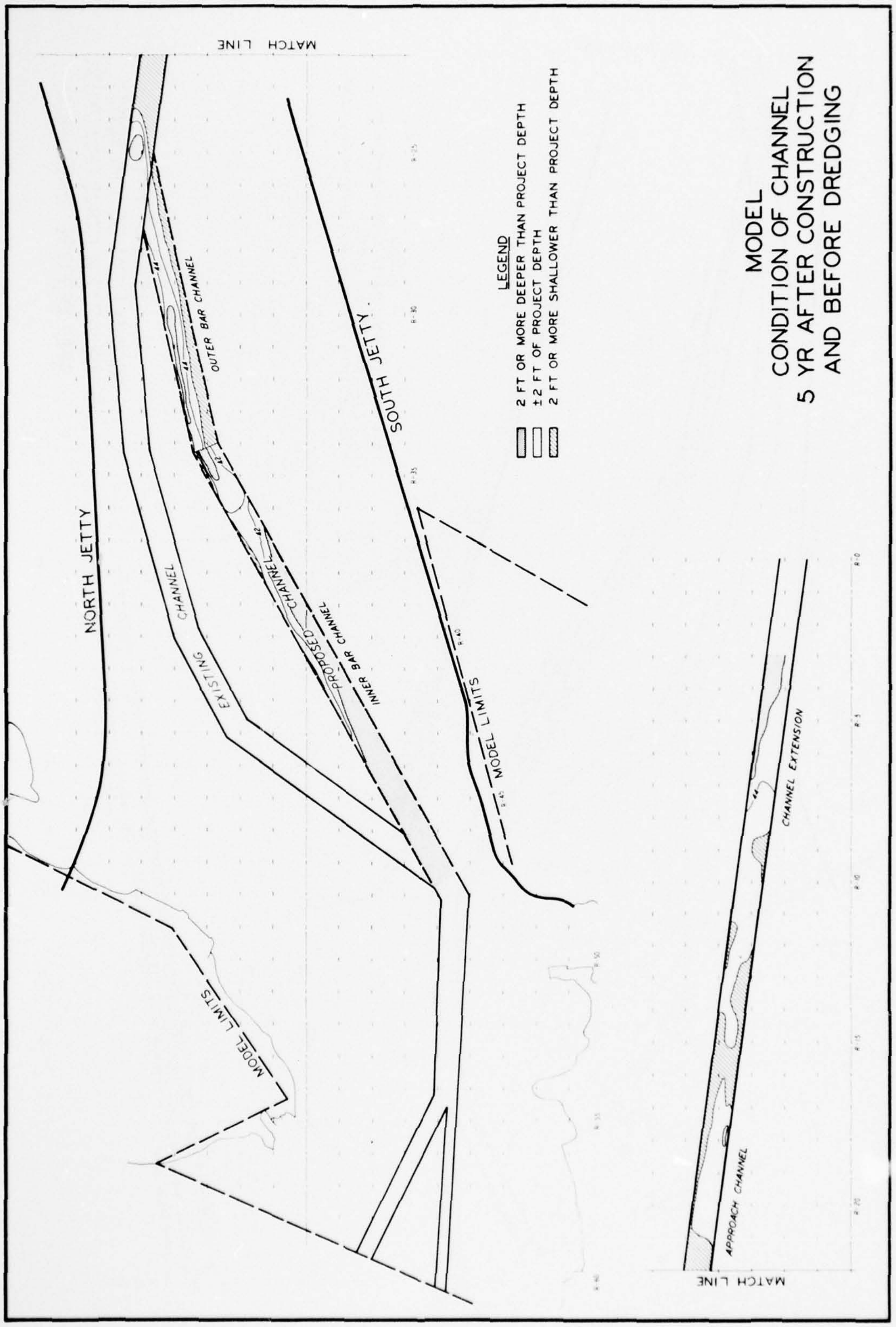
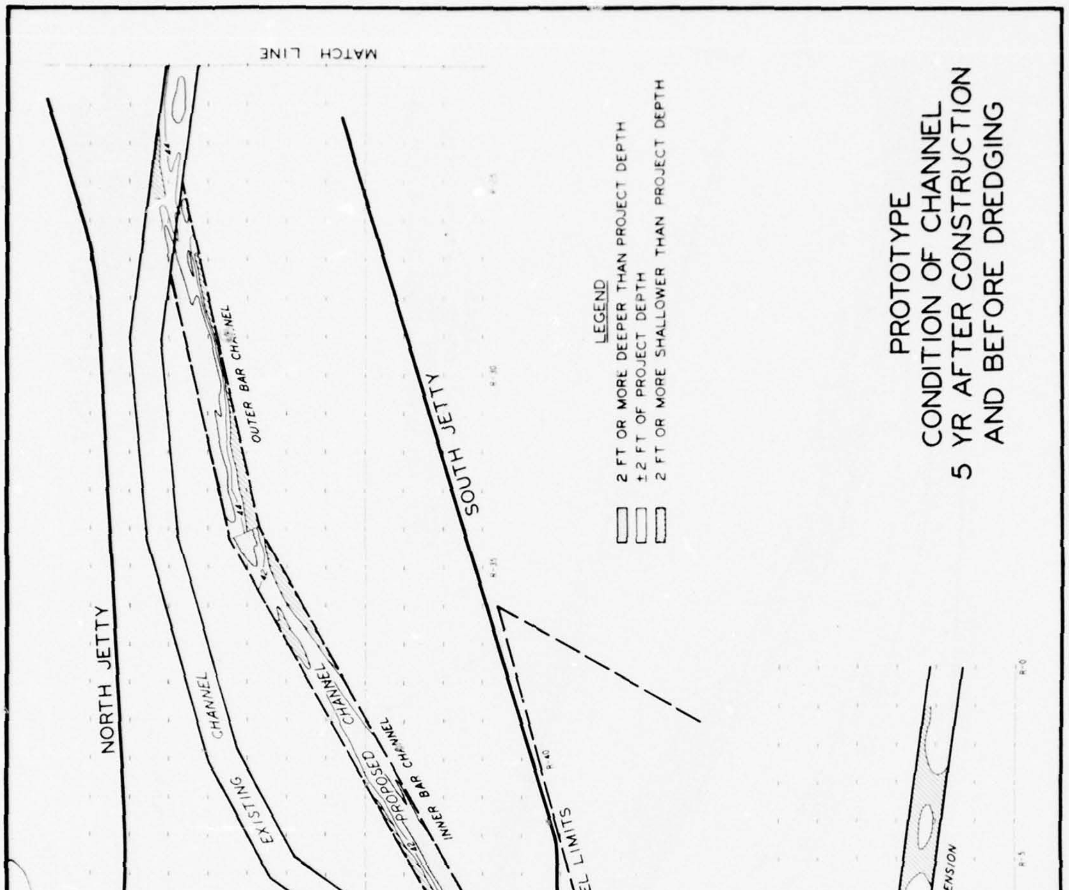

MATCH LINE
NORTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
INNER BAR CHANNEL
OUTER BAR CHANNEL
SOUTH JETTY
MODEL LIMITS
MODEL LIMITS
CHANNEL EXTENSION
APPROACH CHANNEL
MATCH LINE
LEGEND
2 FT OR MORE DEEPER THAN PROJECT DEPTH
±2 FT OF PROJECT DEPTH
2 FT OR MORE SHALLOWER THAN PROJECT DEPTH
PROTOTYPE
CONDITION OF CHANNEL
4 YR AFTER CONSTRUCTION
AND AFTER DREDGING

PLATE 32



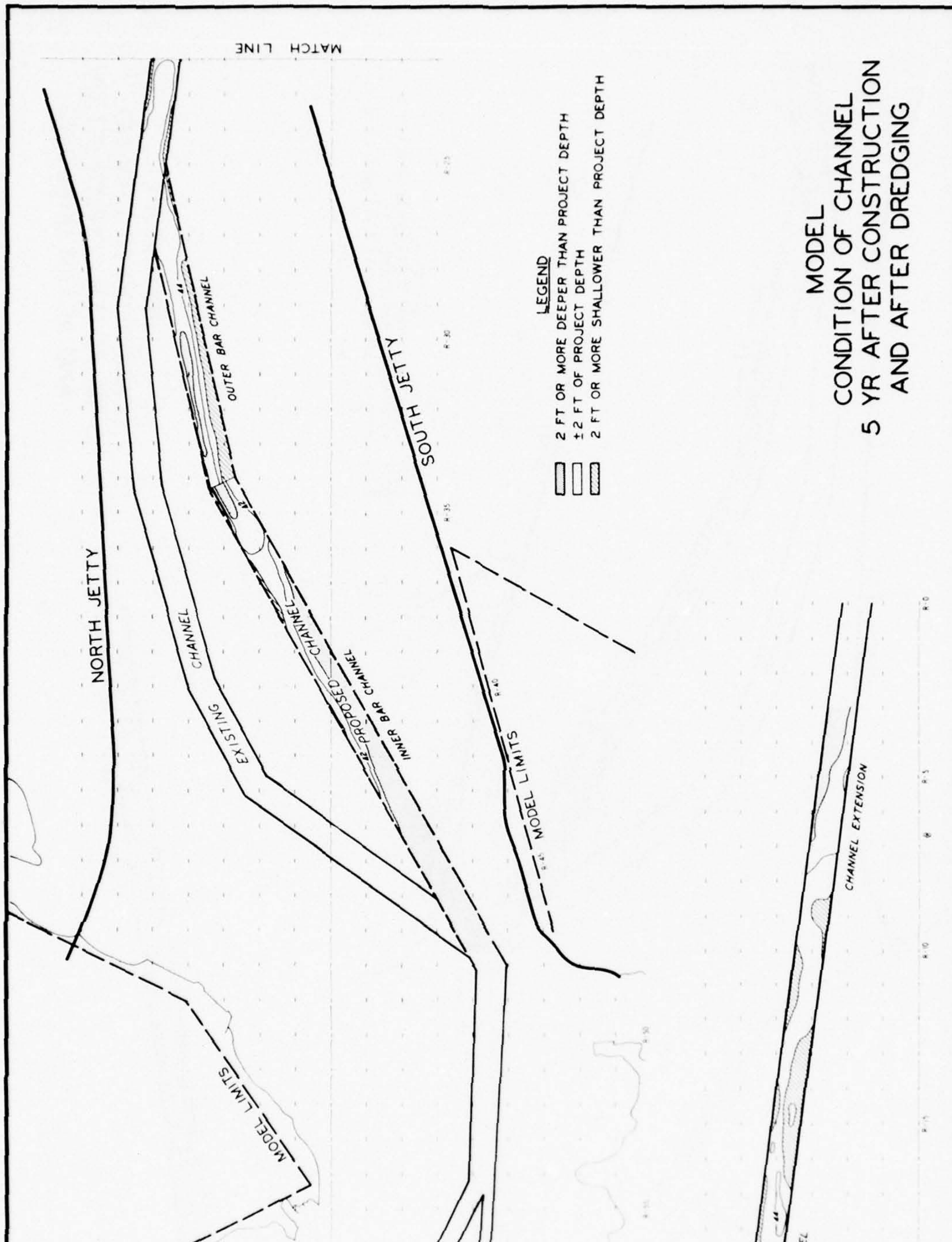
MODEL
CONDITION OF CHANNEL
5 YR AFTER CONSTRUCTION
AND BEFORE DREDGING

PLATE 33

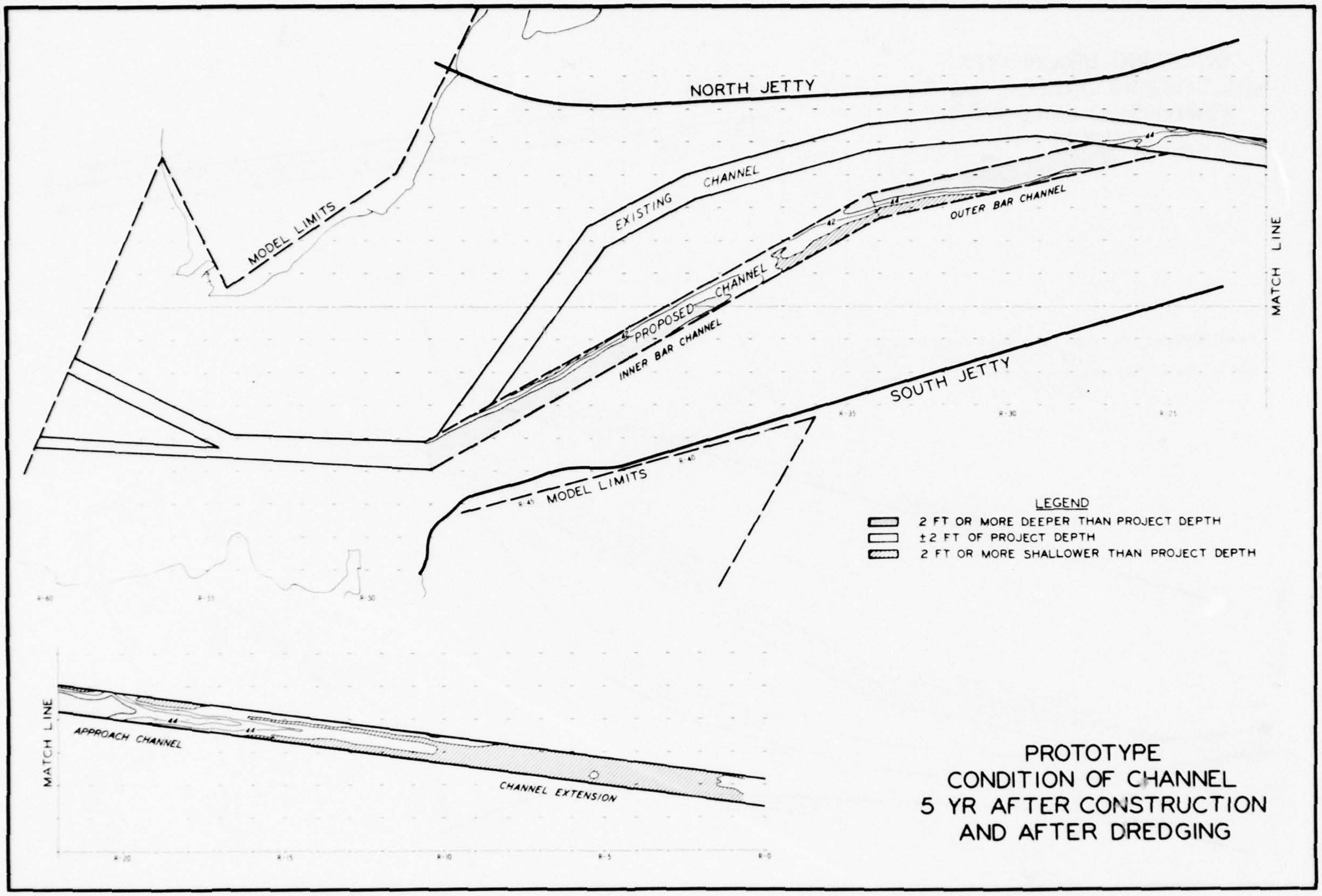


PROTOTYPE
CONDITION OF CHANNEL
5 YR AFTER CONSTRUCTION
AND BEFORE DREDGING

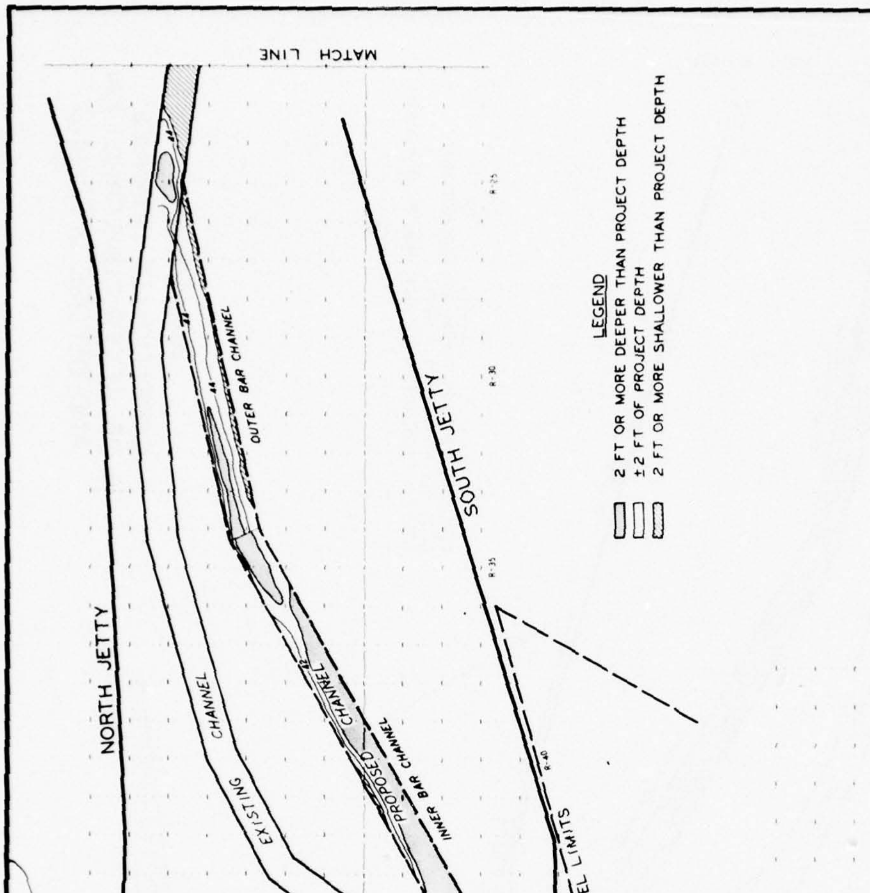
PLATE 34



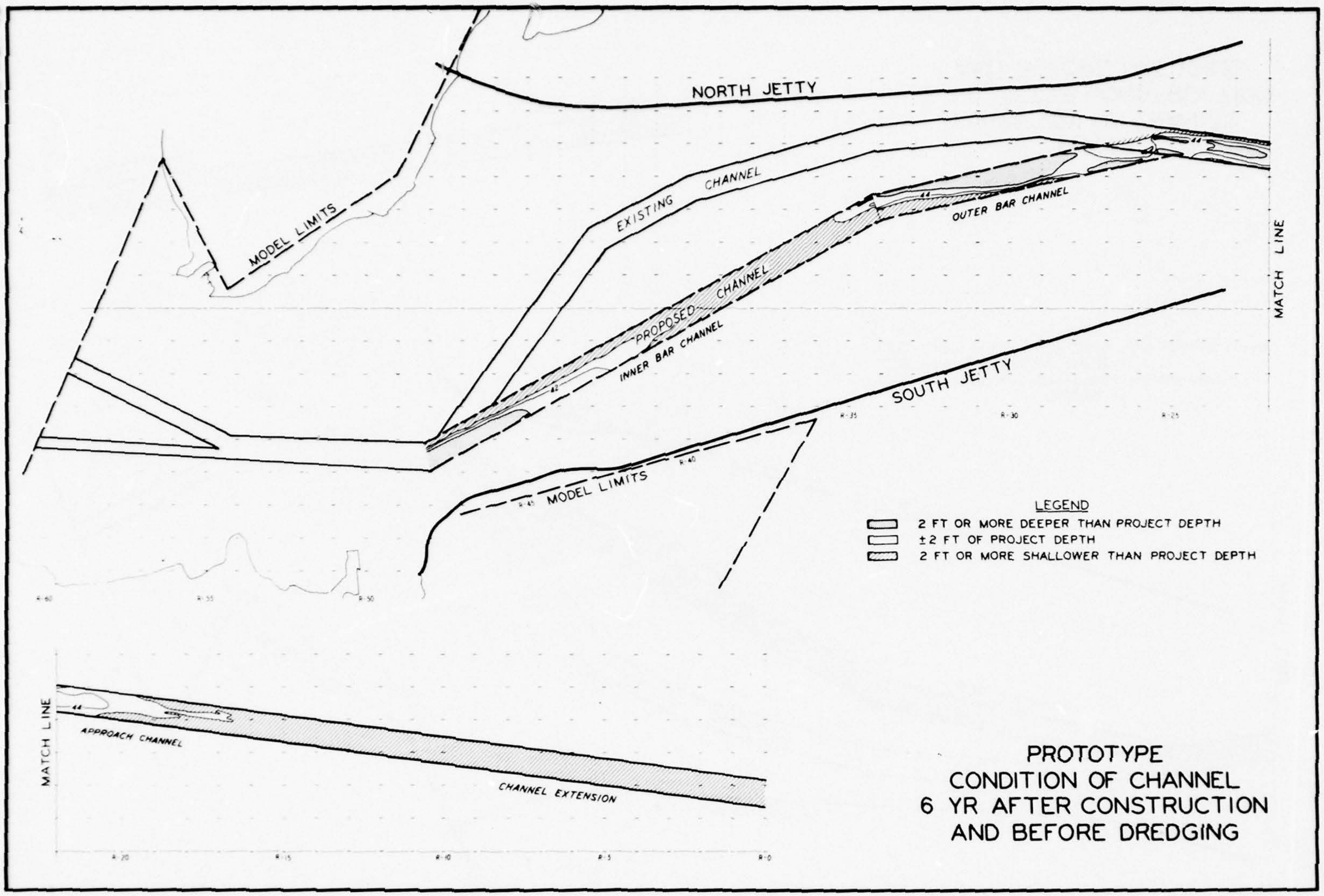
MODEL
CONDITION OF CHANNEL
5 YR AFTER CONSTRUCTION
AND AFTER DREDGING



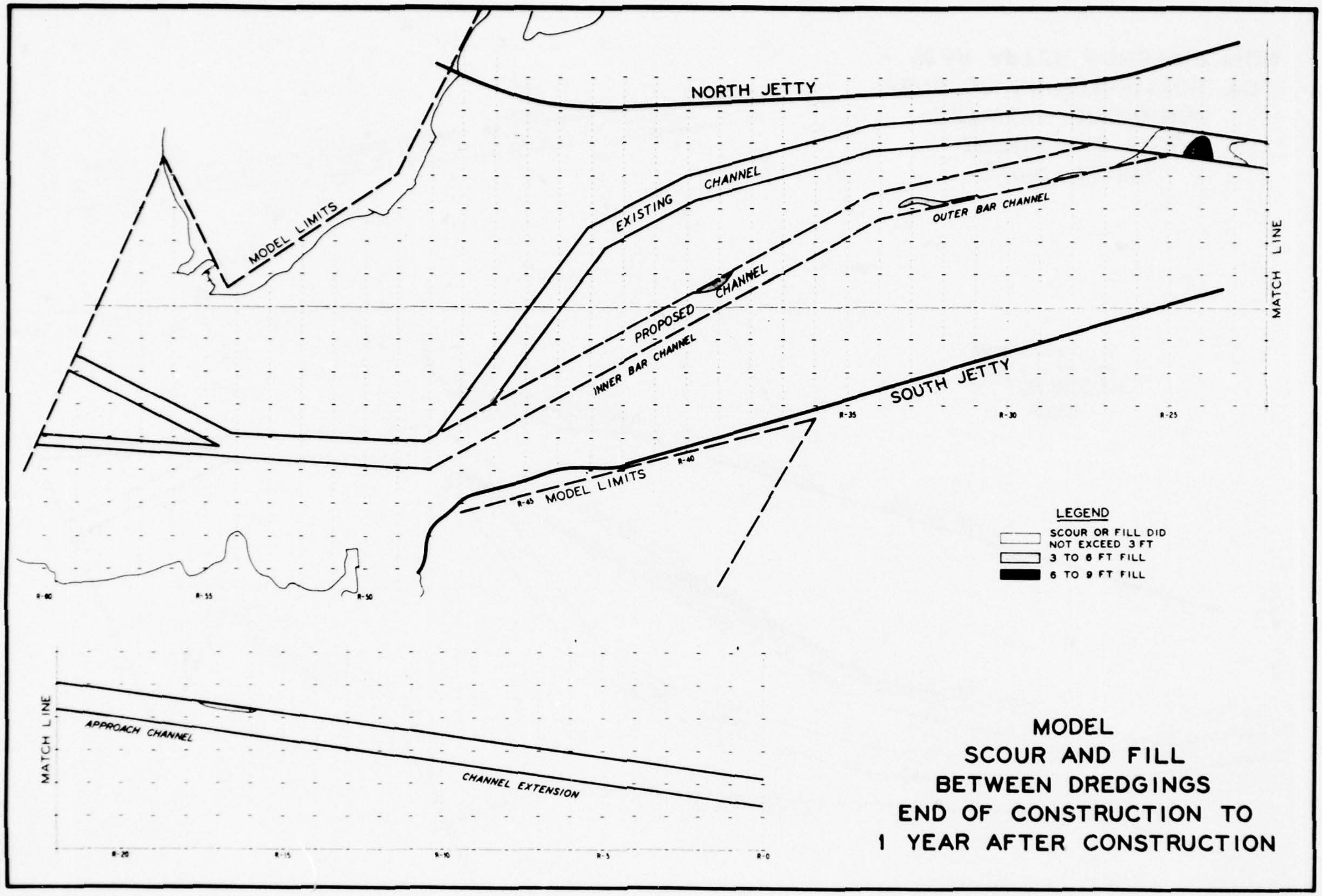
PROTOTYPE
CONDITION OF CHANNEL
5 YR AFTER CONSTRUCTION
AND AFTER DREDGING



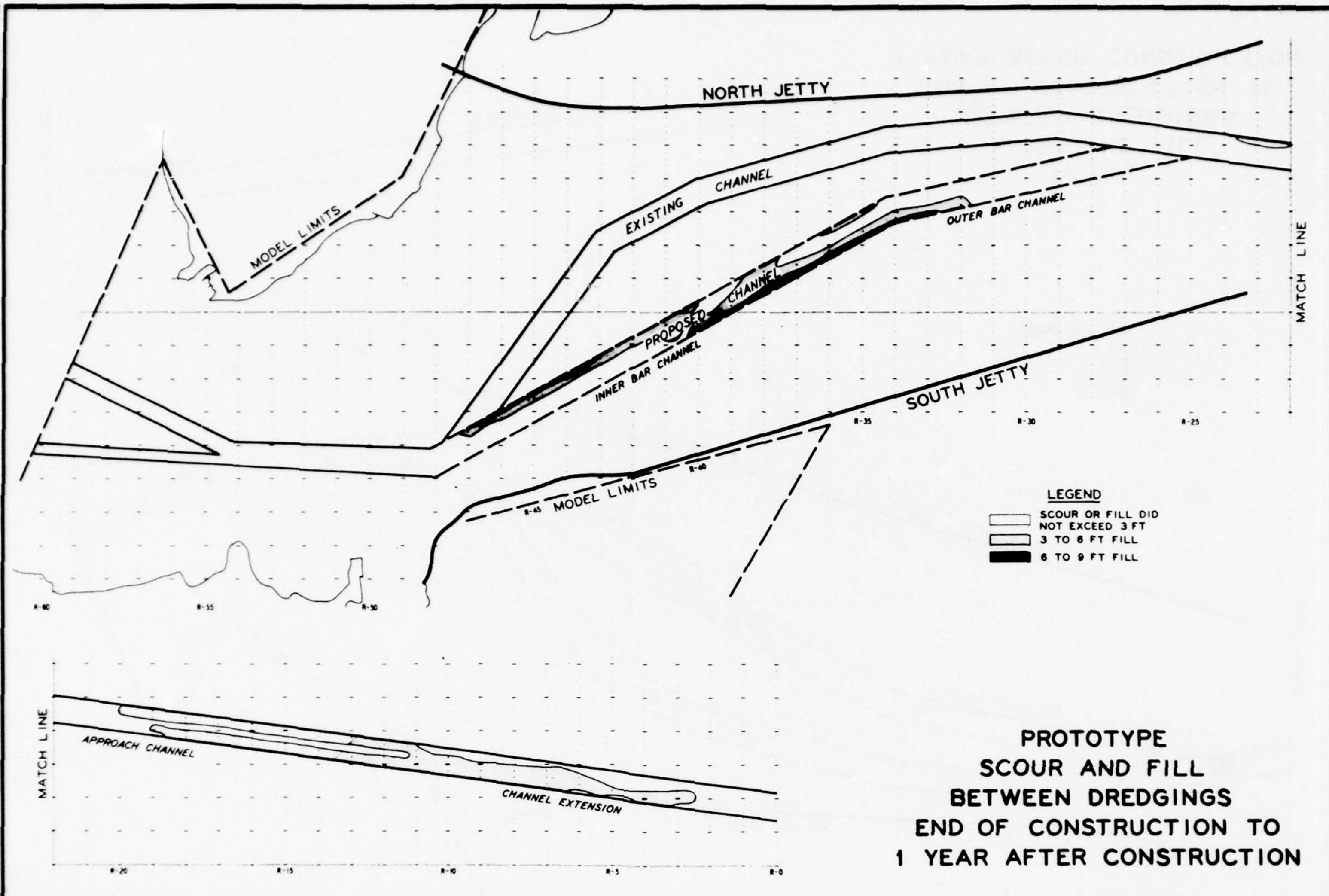
MODEL
CONDITION OF CHANNEL
6 YR AFTER CONSTRUCTION
AND BEFORE DREDGING



PROTOTYPE
CONDITION OF CHANNEL
6 YR AFTER CONSTRUCTION
AND BEFORE DREDGING



MODEL
SCOUR AND FILL
BETWEEN DREDGINGS
END OF CONSTRUCTION TO
1 YEAR AFTER CONSTRUCTION



PROTOTYPE
SCOUR AND FILL
BETWEEN DREDGINGS
END OF CONSTRUCTION TO
1 YEAR AFTER CONSTRUCTION

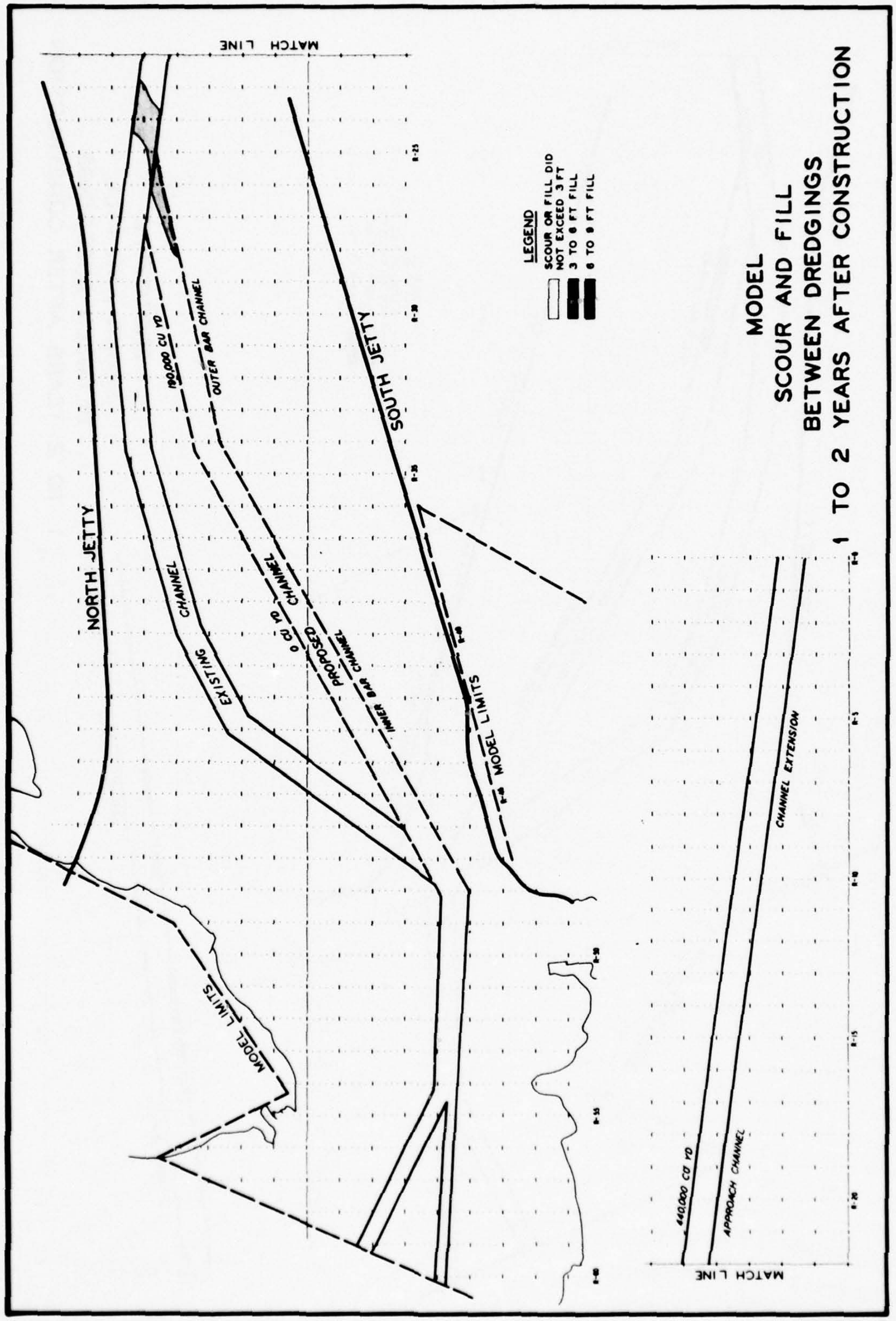
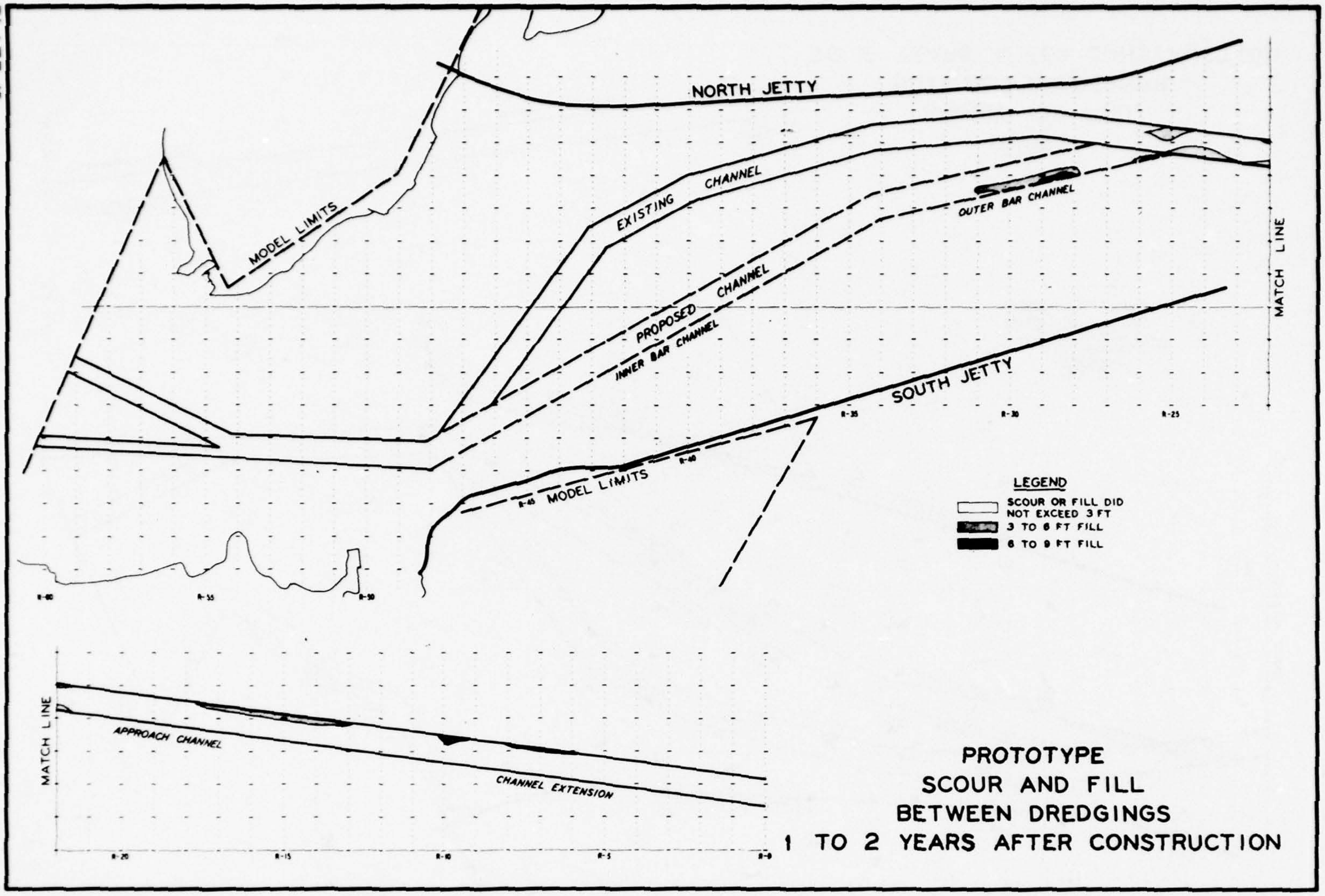
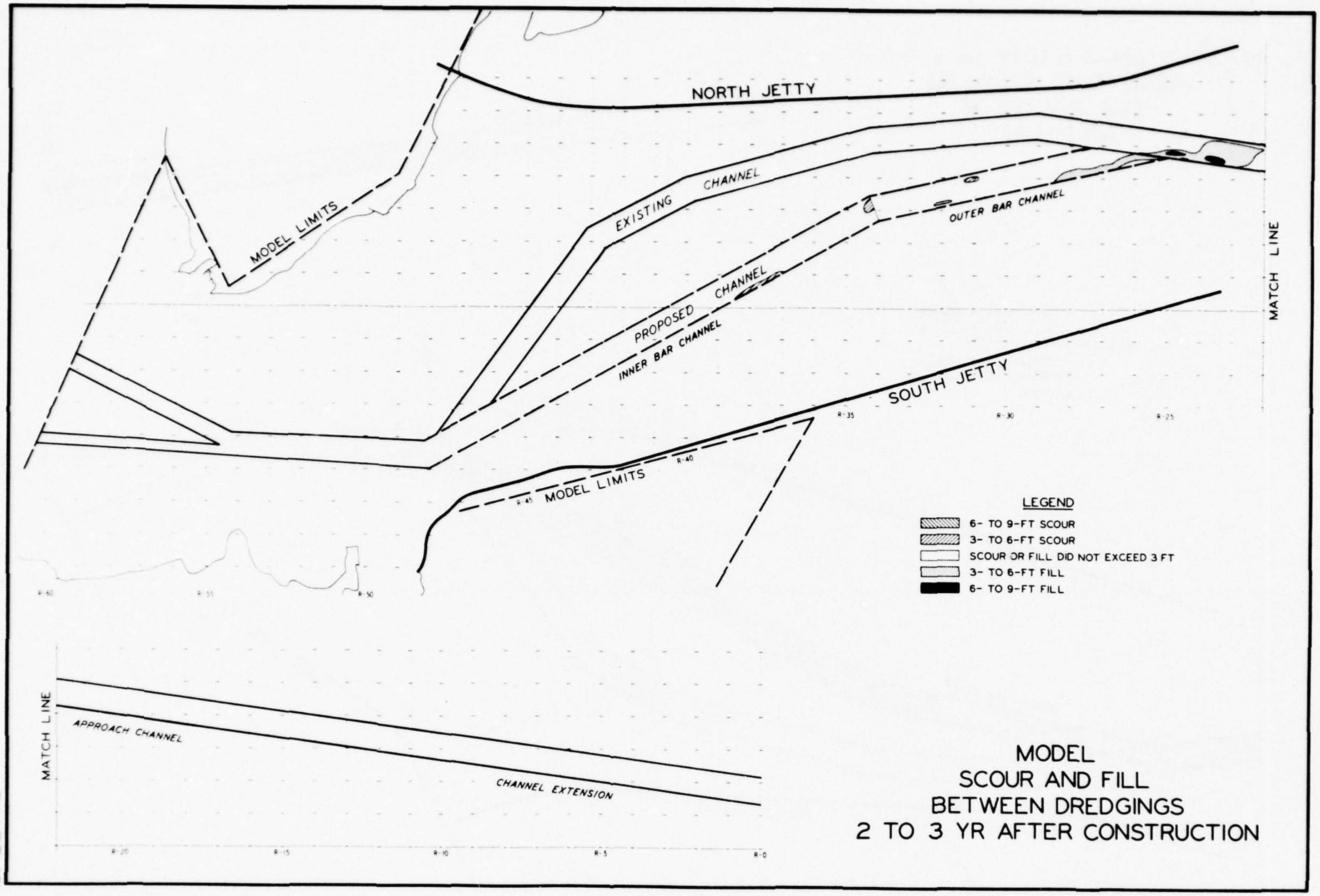

MATCH LINE
NORTH JETTY
EXISTING CHANNEL
0 CU YD
PROPOSED CHANNEL
INNER BAR CHANNEL
190,000 CU YD
OUTER BAR CHANNEL
SOUTH JETTY
MODEL LIMITS
MODEL LIMITS
LEGEND
SCOUR OR FILL DID NOT EXCEED 3 FT
3 TO 6 FT FILL
6 TO 9 FT FILL
440,000 CU YD
APPROACH CHANNEL
CHANNEL EXTENSION
MATCH LINE
MODEL
SCOUR AND FILL
BETWEEN DREDGINGS
1 TO 2 YEARS AFTER CONSTRUCTION

PLATE 41

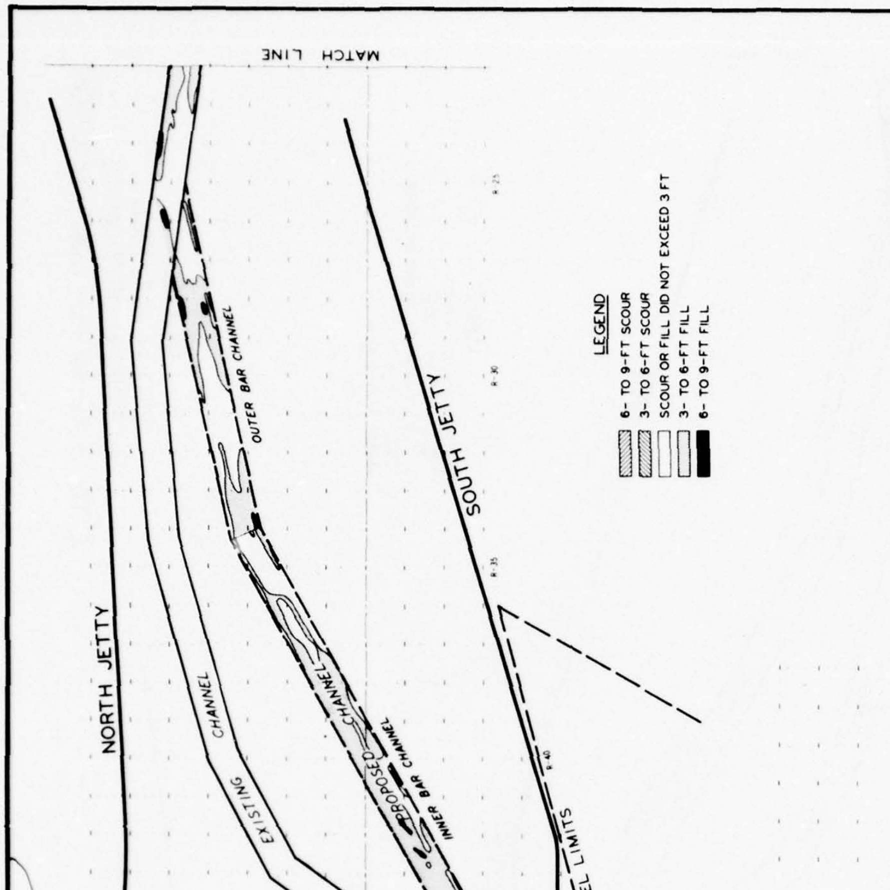


PROTOTYPE
SCOUR AND FILL
BETWEEN DREDGINGS
1 TO 2 YEARS AFTER CONSTRUCTION

PLATE 42

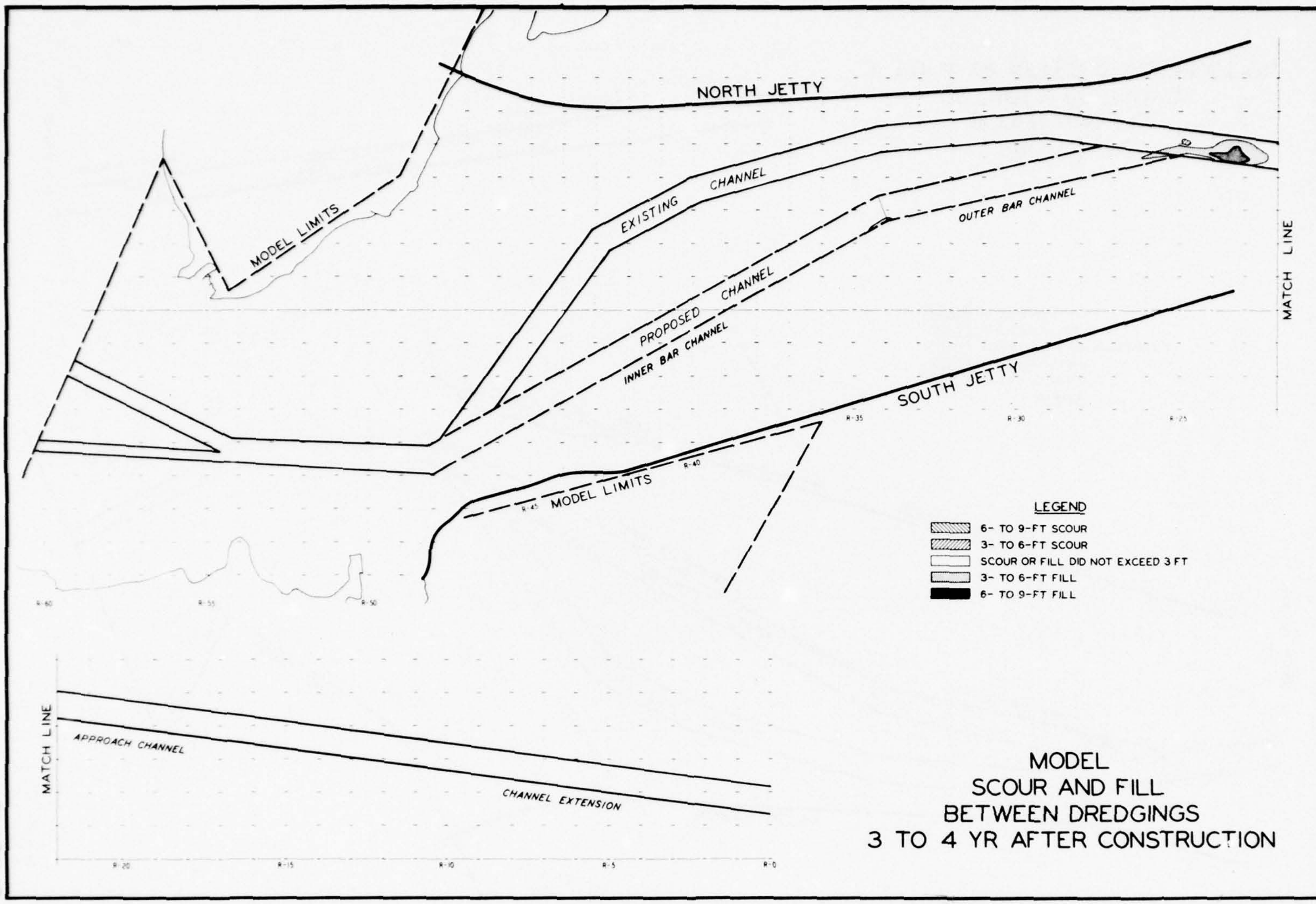


MODEL
SCOUR AND FILL
BETWEEN DREDGINGS
2 TO 3 YR AFTER CONSTRUCTION



PROTOTYPE
SCOUR AND FILL
BETWEEN DREDGINGS
2 TO 3 YR AFTER CONSTRUCTION

PLATE 44



MODEL
SCOUR AND FILL
BETWEEN DREDGINGS
3 TO 4 YR AFTER CONSTRUCTION

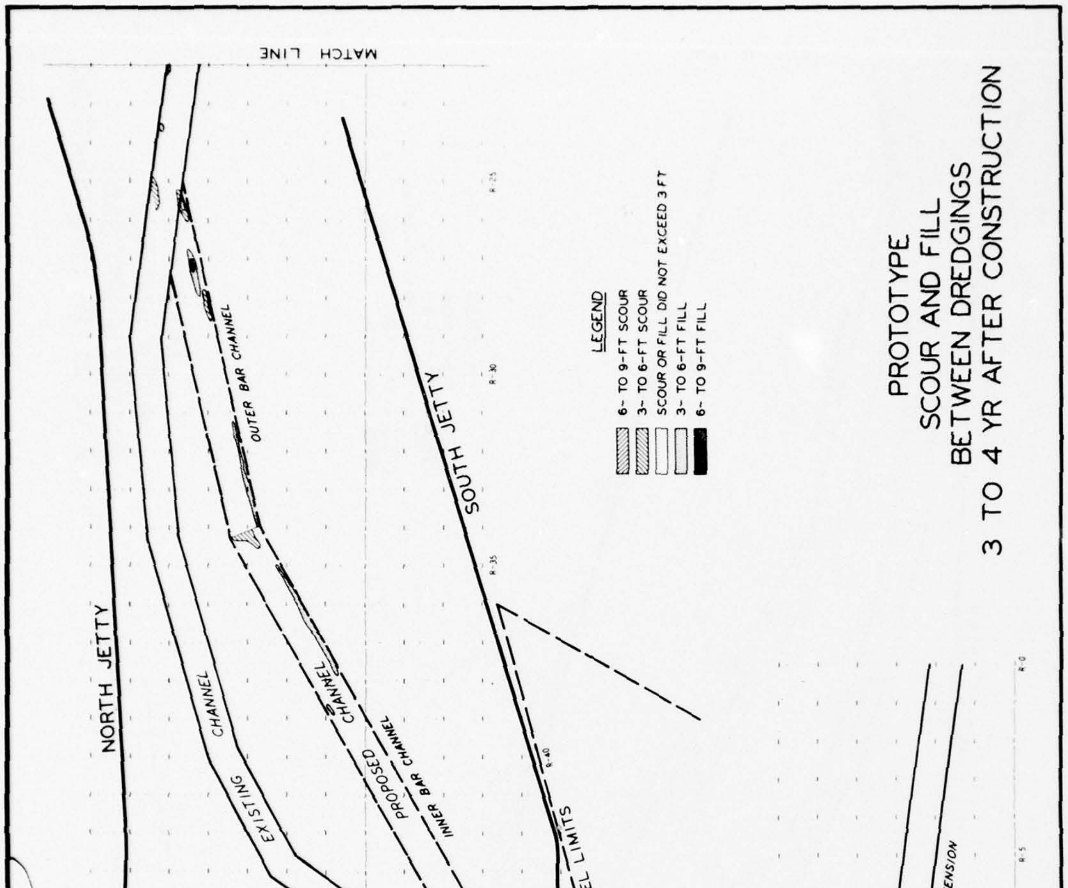
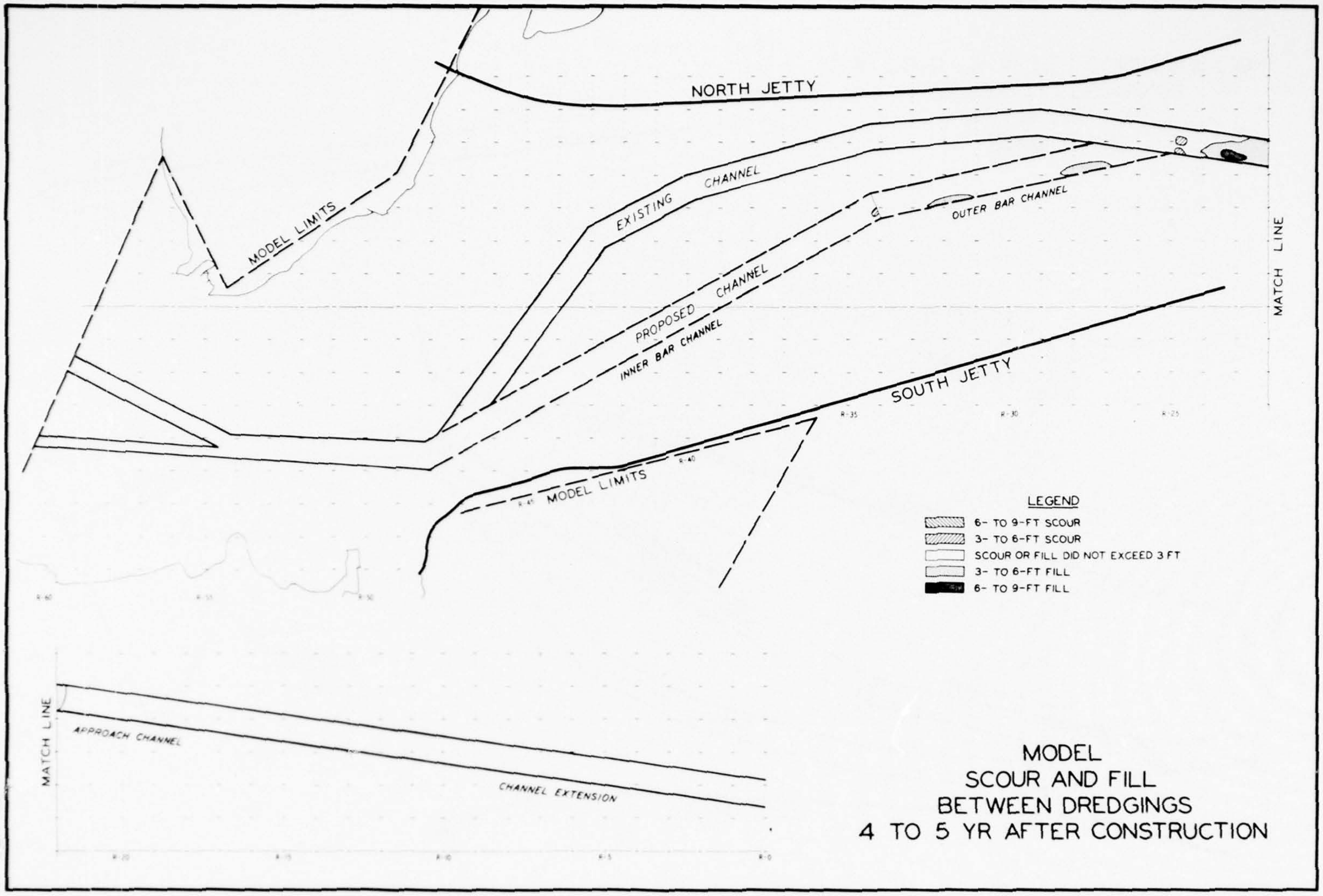
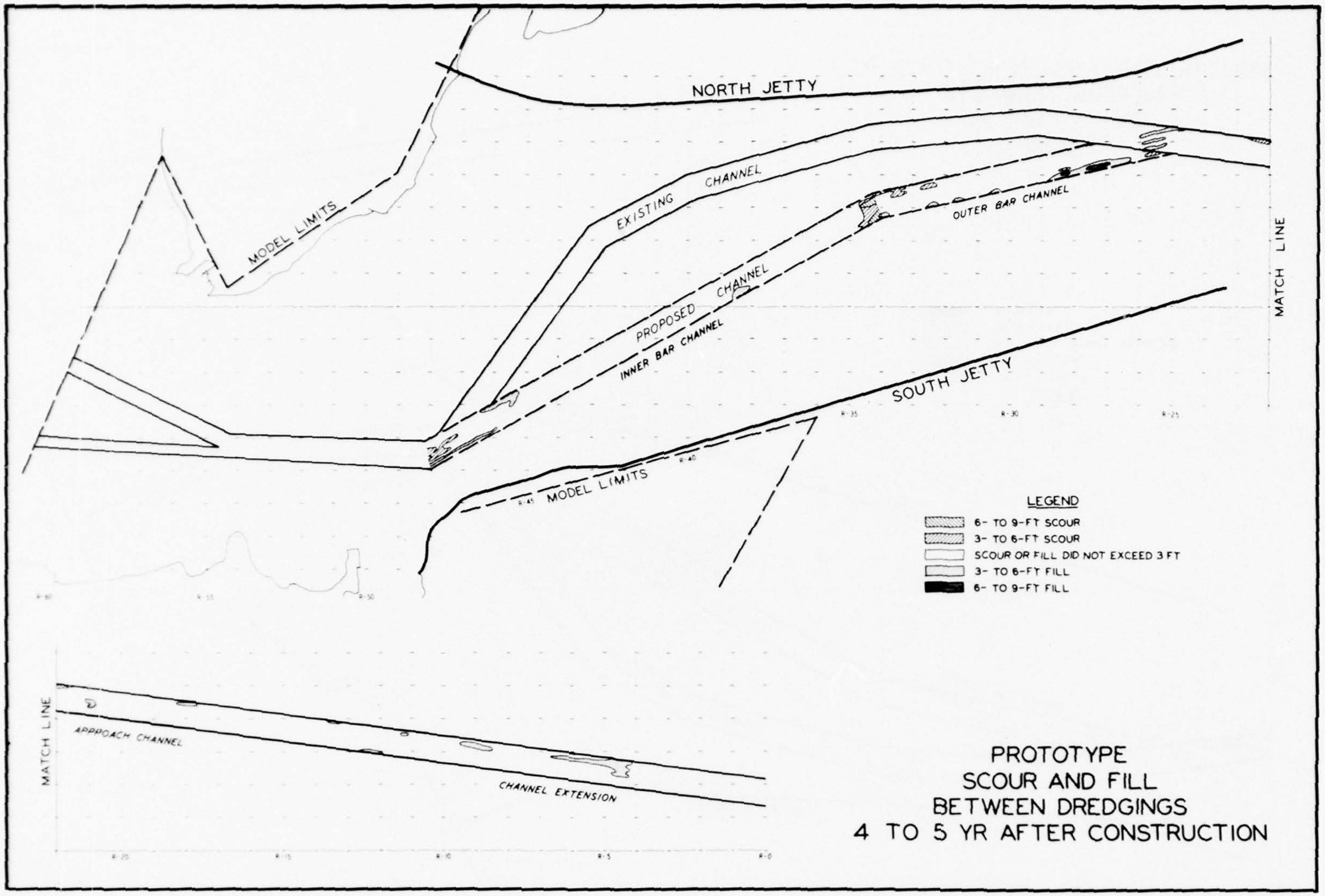

PROTOTYPE
SCOUR AND FILL
BETWEEN DREDGINGS
3 TO 4 YR AFTER CONSTRUCTION
LEGEND
6- TO 9-FT SCOUR
3- TO 6-FT SCOUR
SCOUR OR FILL DID NOT EXCEED 3 FT
3- TO 6-FT FILL
6- TO 9-FT FILL
NORTH JETTY
SOUTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
INNER BAR CHANNEL
OUTER BAR CHANNEL
MODEL LIMITS
MODEL LIMITS
MATCH LINE
MATCH LINE
APPROACH CHANNEL
CHANNEL EXTENSION

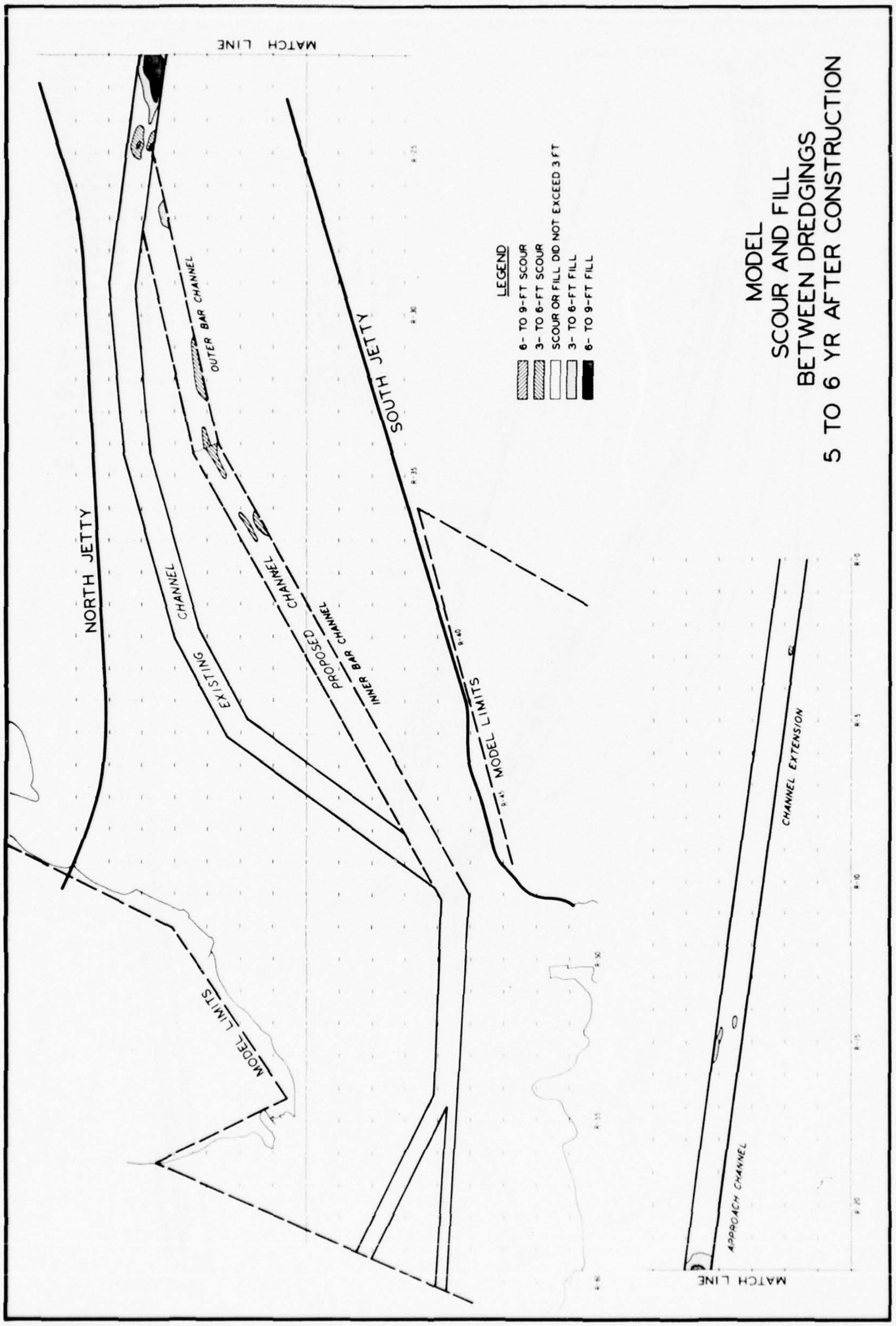
PLATE 46



MODEL
SCOUR AND FILL
BETWEEN DREDGINGS
4 TO 5 YR AFTER CONSTRUCTION

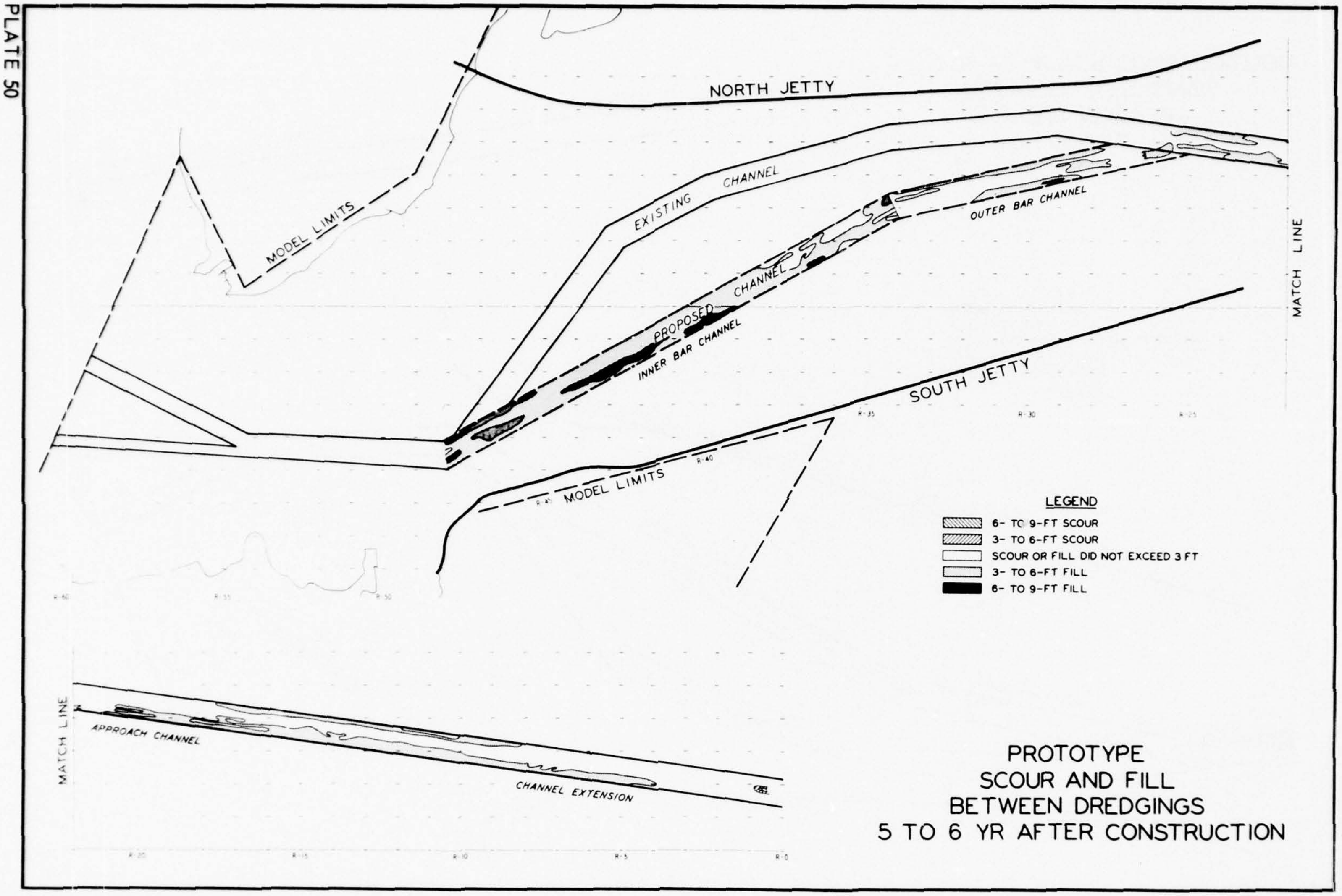


PROTOTYPE
SCOUR AND FILL
BETWEEN DREDGINGS
4 TO 5 YR AFTER CONSTRUCTION

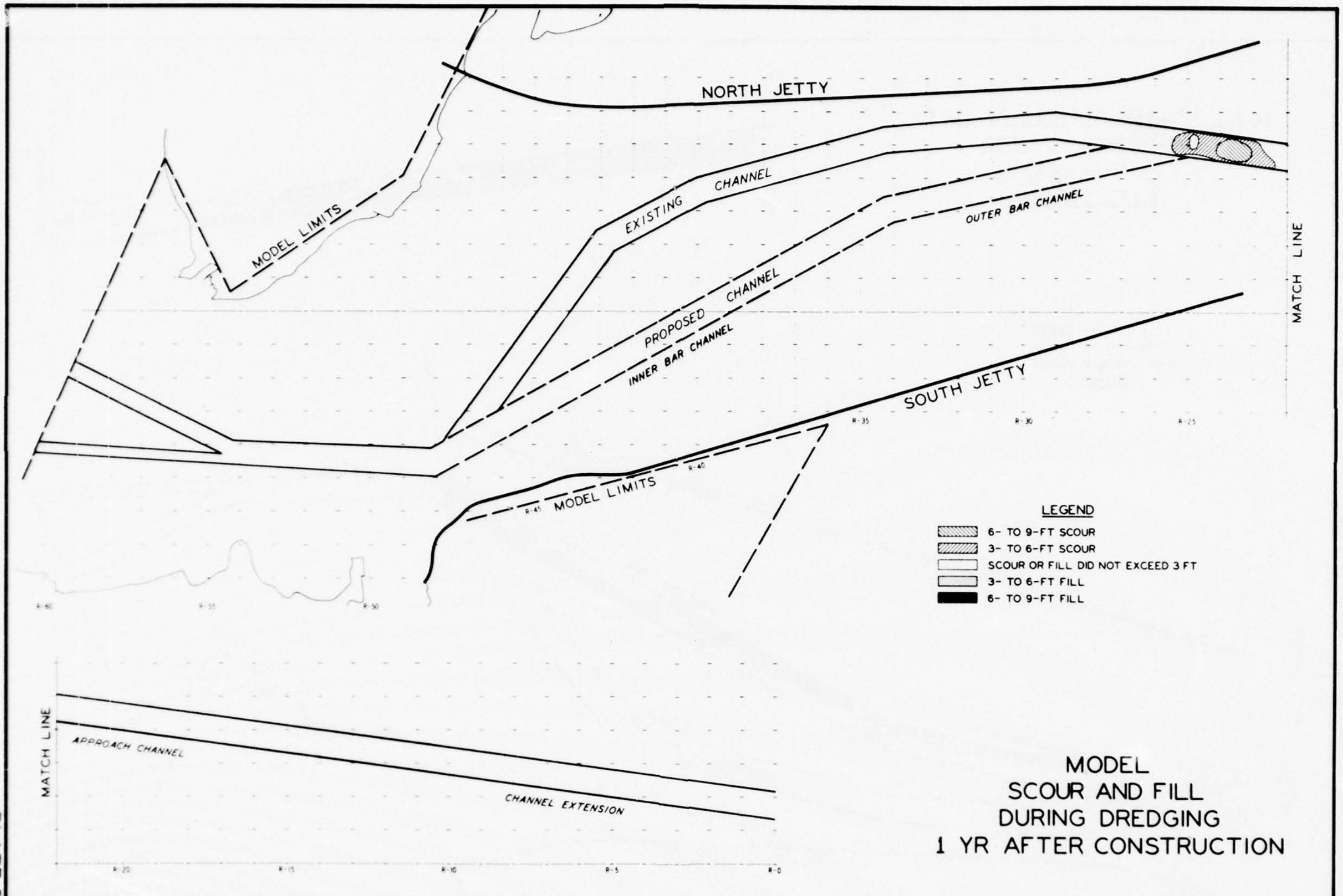


MODEL
SCOUR AND FILL
BETWEEN DREDGINGS
5 TO 6 YR AFTER CONSTRUCTION
LEGEND
6- TO 9-FT SCOUR
3- TO 6-FT SCOUR
SCOUR OR FILL DID NOT EXCEED 3 FT
3- TO 6-FT FILL
6- TO 9-FT FILL
NORTH JETTY
SOUTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
INNER BAR CHANNEL
OUTER BAR CHANNEL
MODEL LIMITS
MODEL LIMITS
CHANNEL EXTENSION
APPROACH CHANNEL
MATCH LINE
MATCH LINE

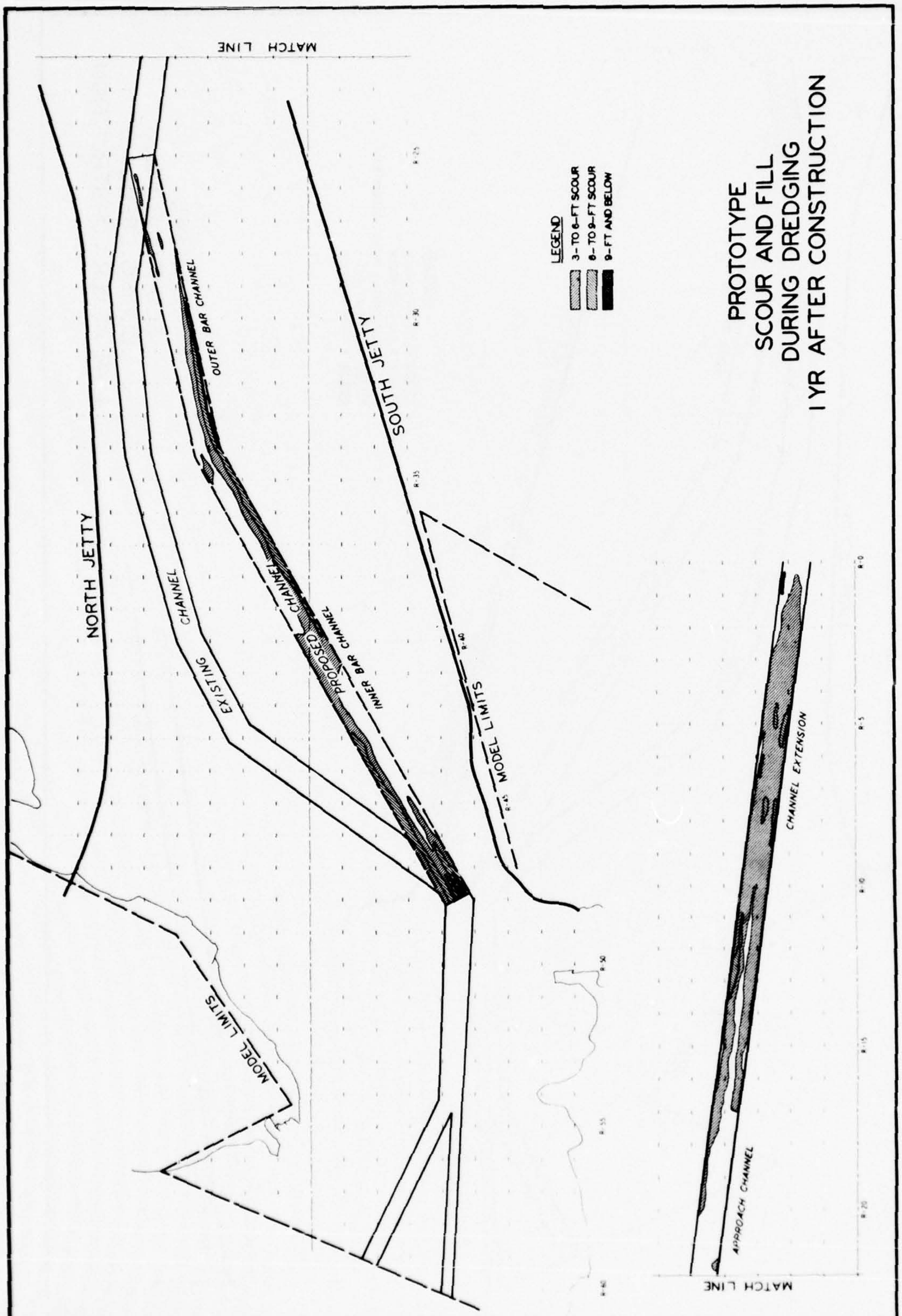
PLATE 49



PROTOTYPE
SCOUR AND FILL
BETWEEN DREDGINGS
5 TO 6 YR AFTER CONSTRUCTION

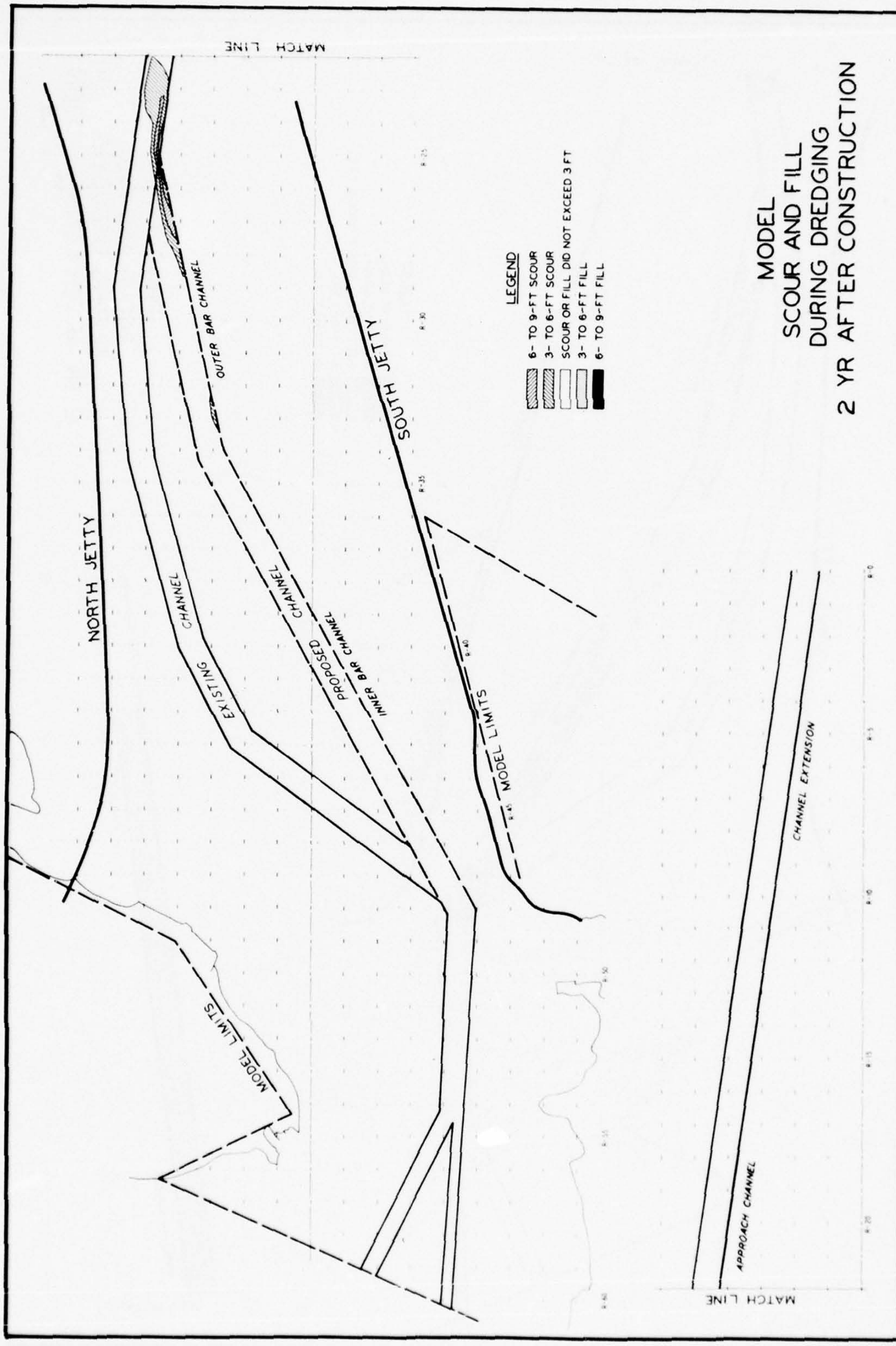


MODEL
SCOUR AND FILL
DURING DREDGING
1 YR AFTER CONSTRUCTION

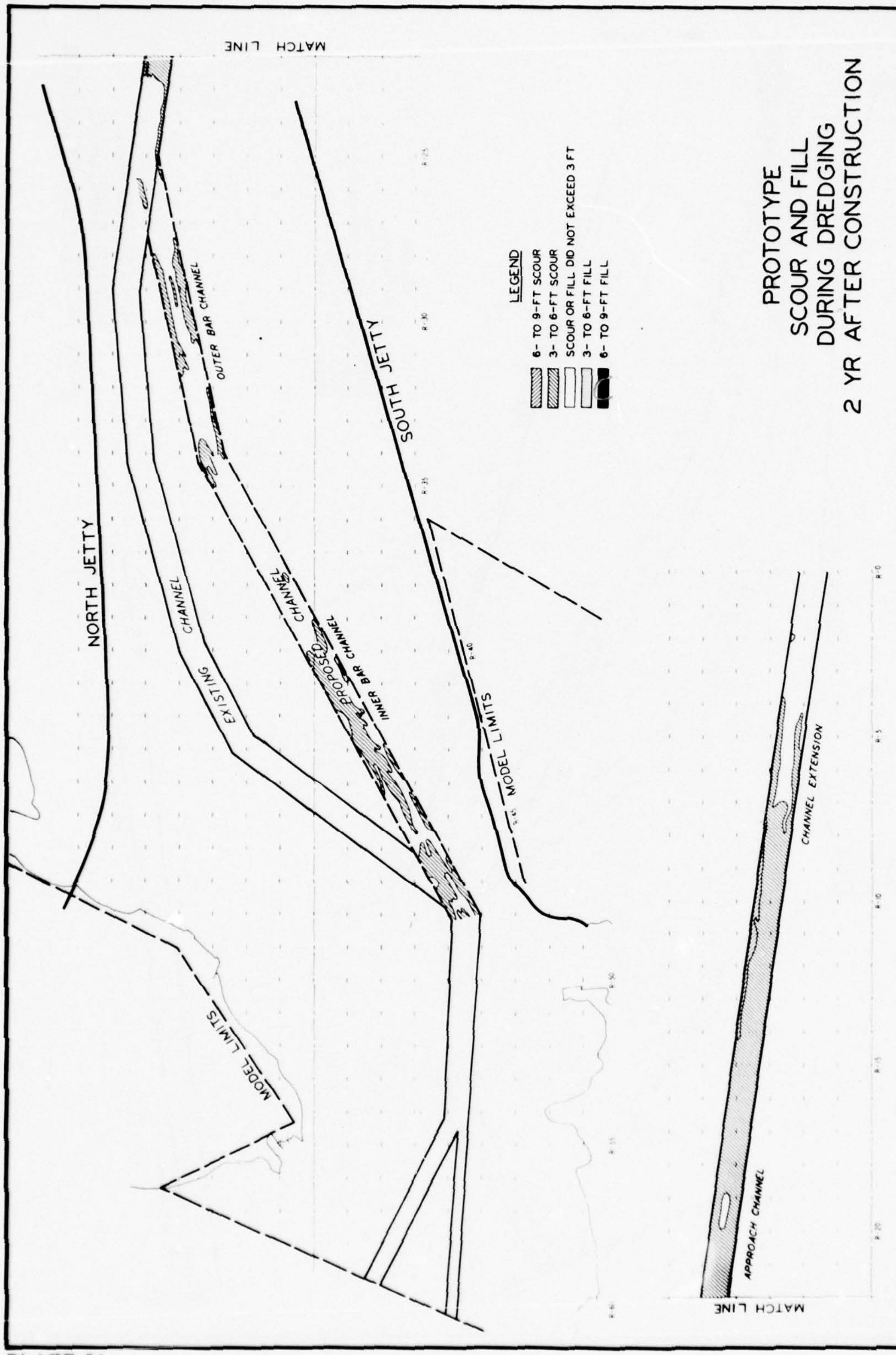


PROTOTYPE
SCOUR AND FILL
DURING DREDGING
1 YR AFTER CONSTRUCTION
LEGEND
3- TO 6-FT SCOUR
6- TO 9-FT SCOUR
9-FT AND BELOW
NORTH JETTY
SOUTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
OUTER BAR CHANNEL
INNER BAR CHANNEL
MODEL LIMITS
MODEL LIMITS
MATCH LINE
MATCH LINE
CHANNEL EXTENSION
APPROACH CHANNEL

PLATE 52

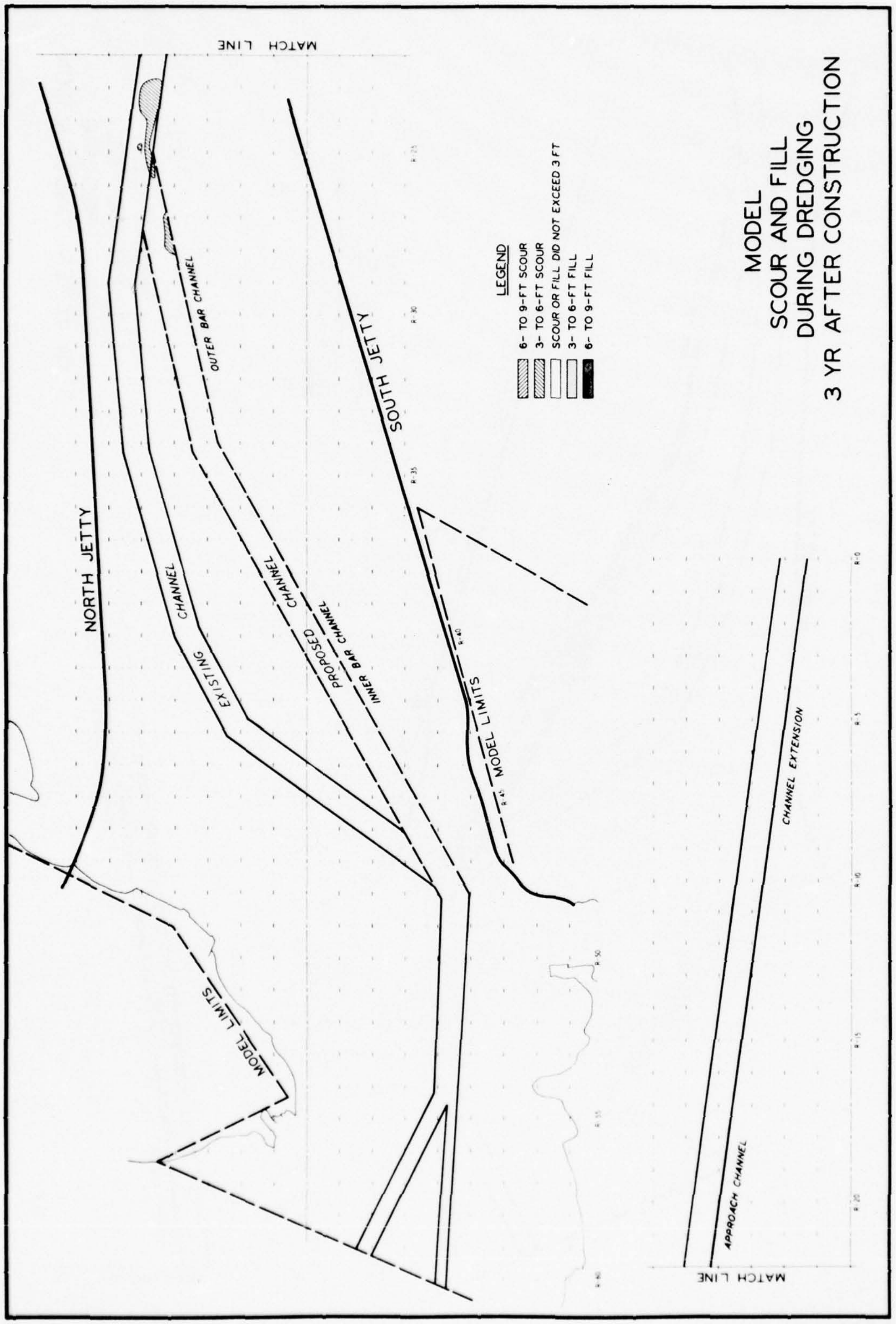


MODEL
SCOUR AND FILL
DURING DREDGING
2 YR AFTER CONSTRUCTION
LEGEND
6- TO 9-FT SCOUR
3- TO 6-FT SCOUR
SCOUR OR FILL DID NOT EXCEED 3 FT
3- TO 6-FT FILL
6- TO 9-FT FILL
NORTH JETTY
SOUTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
INNER BAR CHANNEL
OUTER BAR CHANNEL
MODEL LIMITS
MODEL LIMITS
CHANNEL EXTENSION
APPROACH CHANNEL
MATCH LINE
MATCH LINE

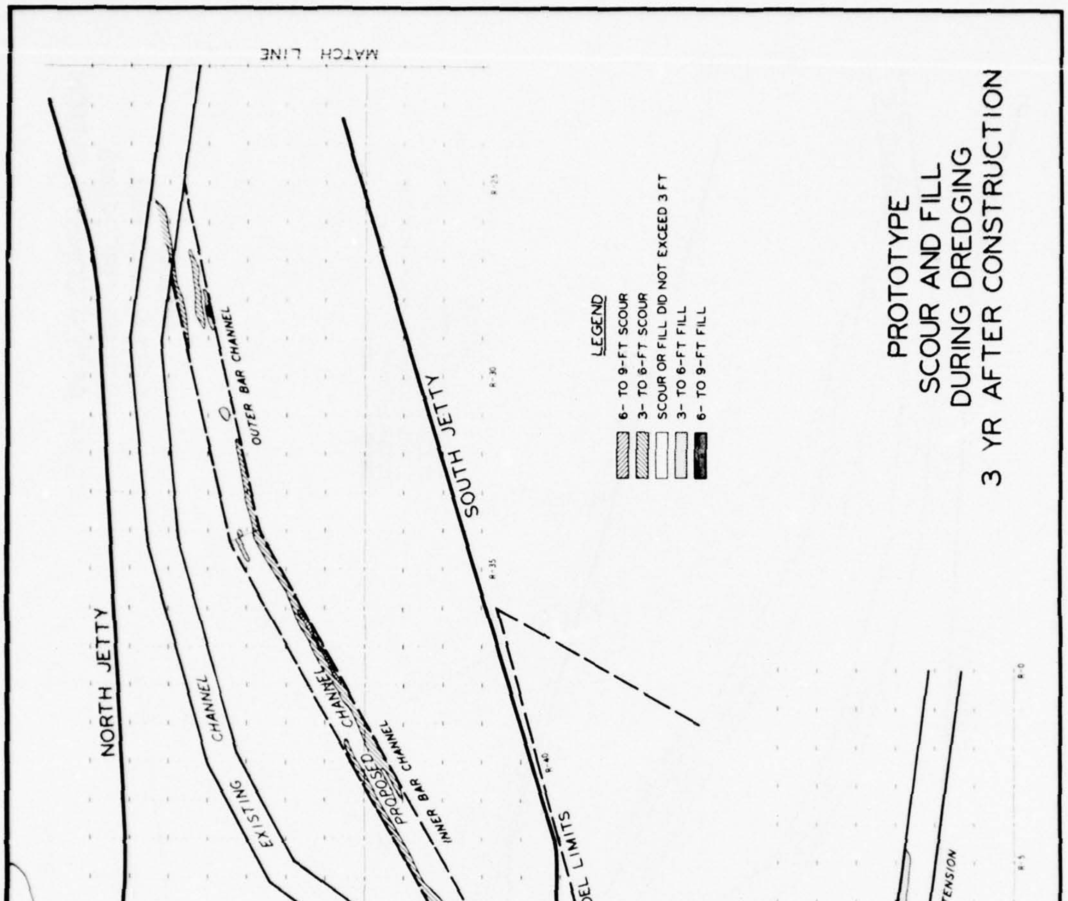


PROTOTYPE
SCOUR AND FILL
DURING DREDGING
2 YR AFTER CONSTRUCTION

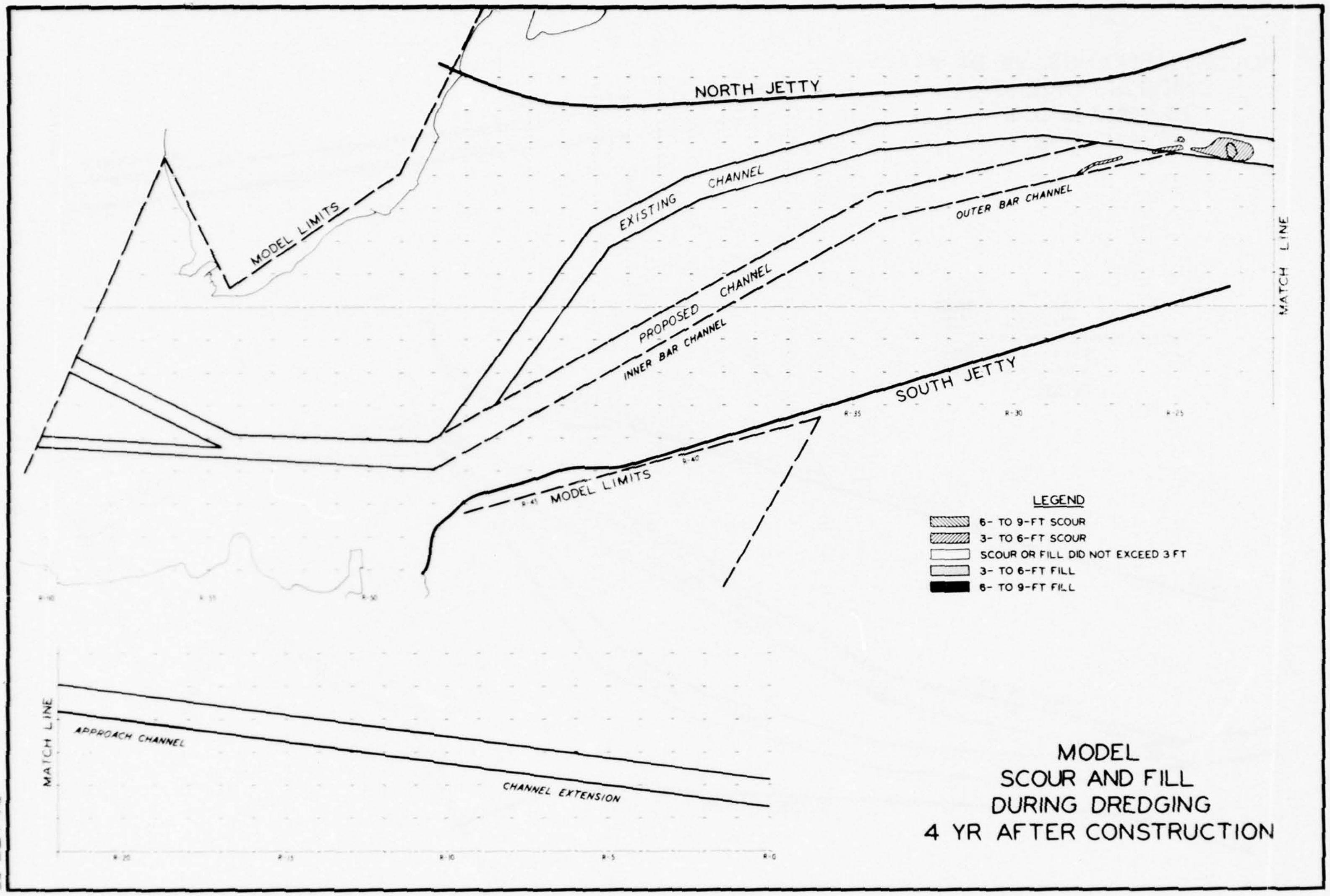
PLATE 54



MODEL
SCOUR AND FILL
DURING DREDGING
3 YR AFTER CONSTRUCTION

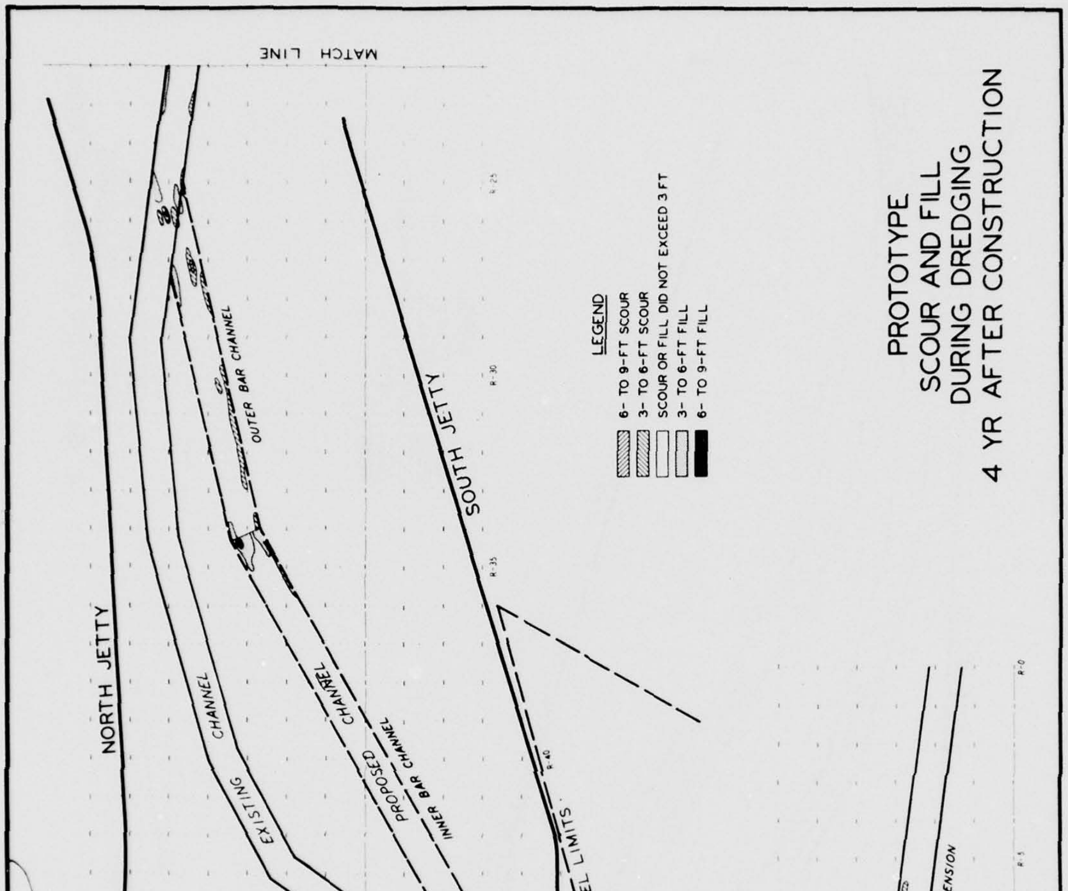


PROTOTYPE
SCOUR AND FILL
DURING DREDGING
3 YR AFTER CONSTRUCTION



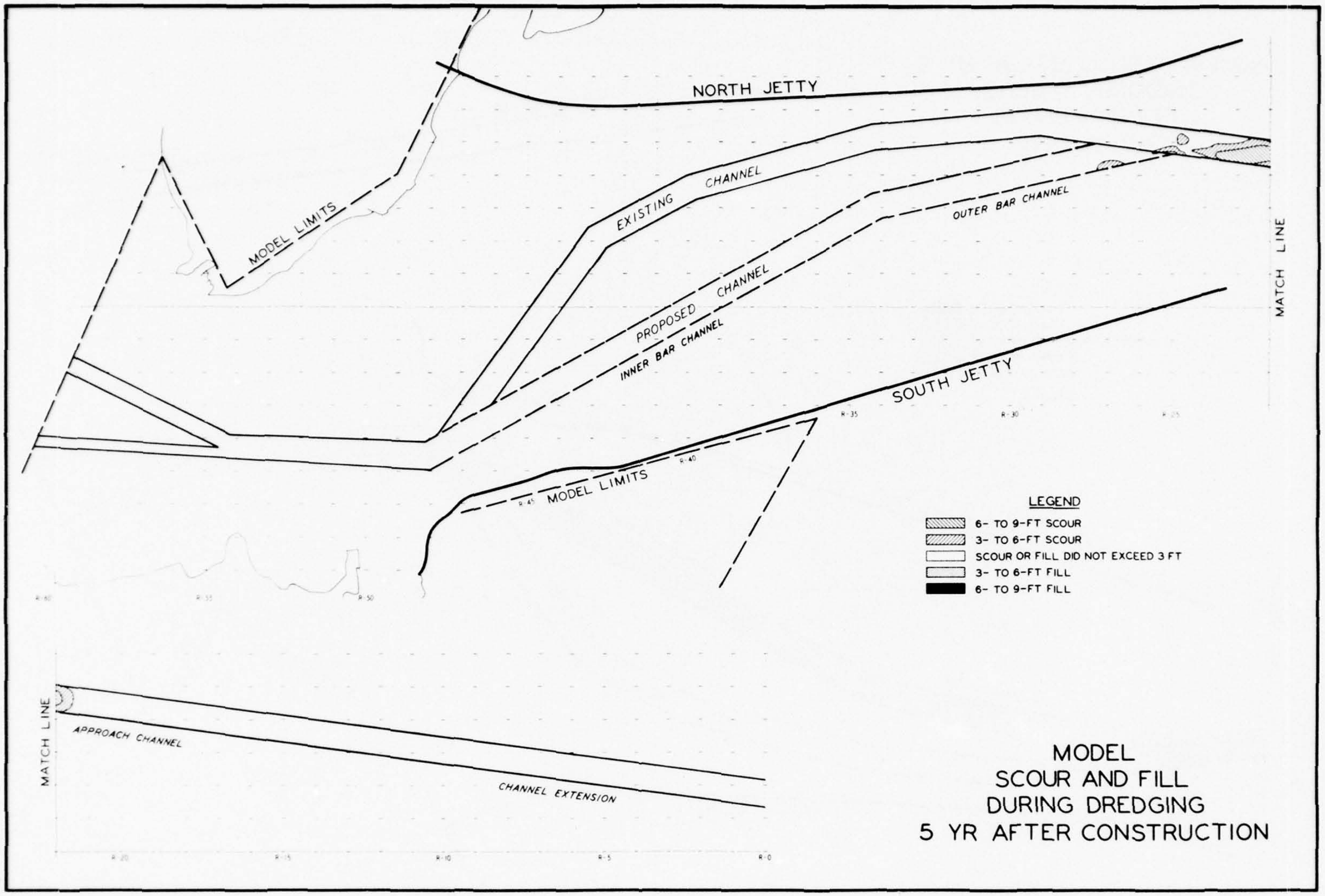
MODEL
SCOUR AND FILL
DURING DREDGING
4 YR AFTER CONSTRUCTION

PLATE 57



PROTOTYPE
SCOUR AND FILL
DURING DREDGING
4 YR AFTER CONSTRUCTION

PLATE 58



MODEL
SCOUR AND FILL
DURING DREDGING
5 YR AFTER CONSTRUCTION

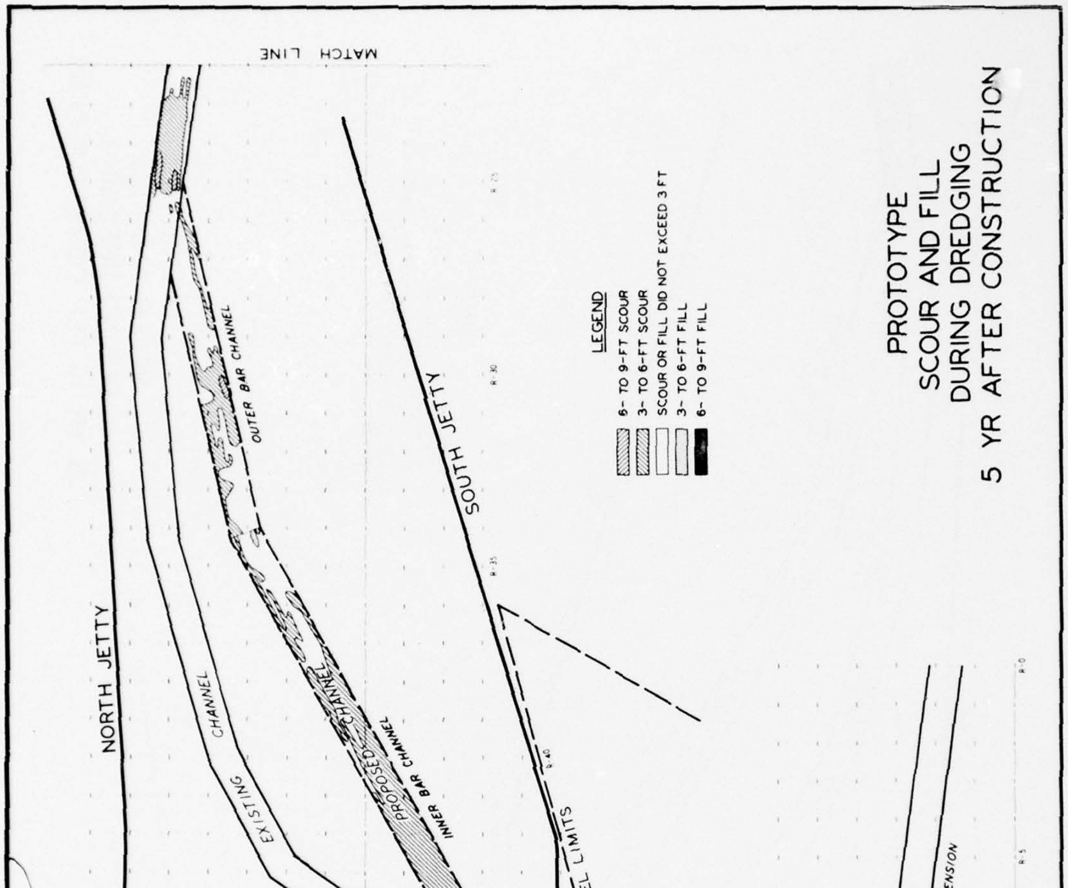

PROTOTYPE
SCOUR AND FILL
DURING DREDGING
5 YR AFTER CONSTRUCTION
LEGEND
6- TO 9-FT SCOUR
3- TO 6-FT SCOUR
SCOUR OR FILL DID NOT EXCEED 3 FT
3- TO 6-FT FILL
6- TO 9-FT FILL
MATCH LINE
NORTH JETTY
SOUTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
OUTER BAR CHANNEL
INNER BAR CHANNEL
MODEL LIMITS
CHANNEL EXTENSION
APPROACH CHANNEL
MATCH LINE

PLATE 60

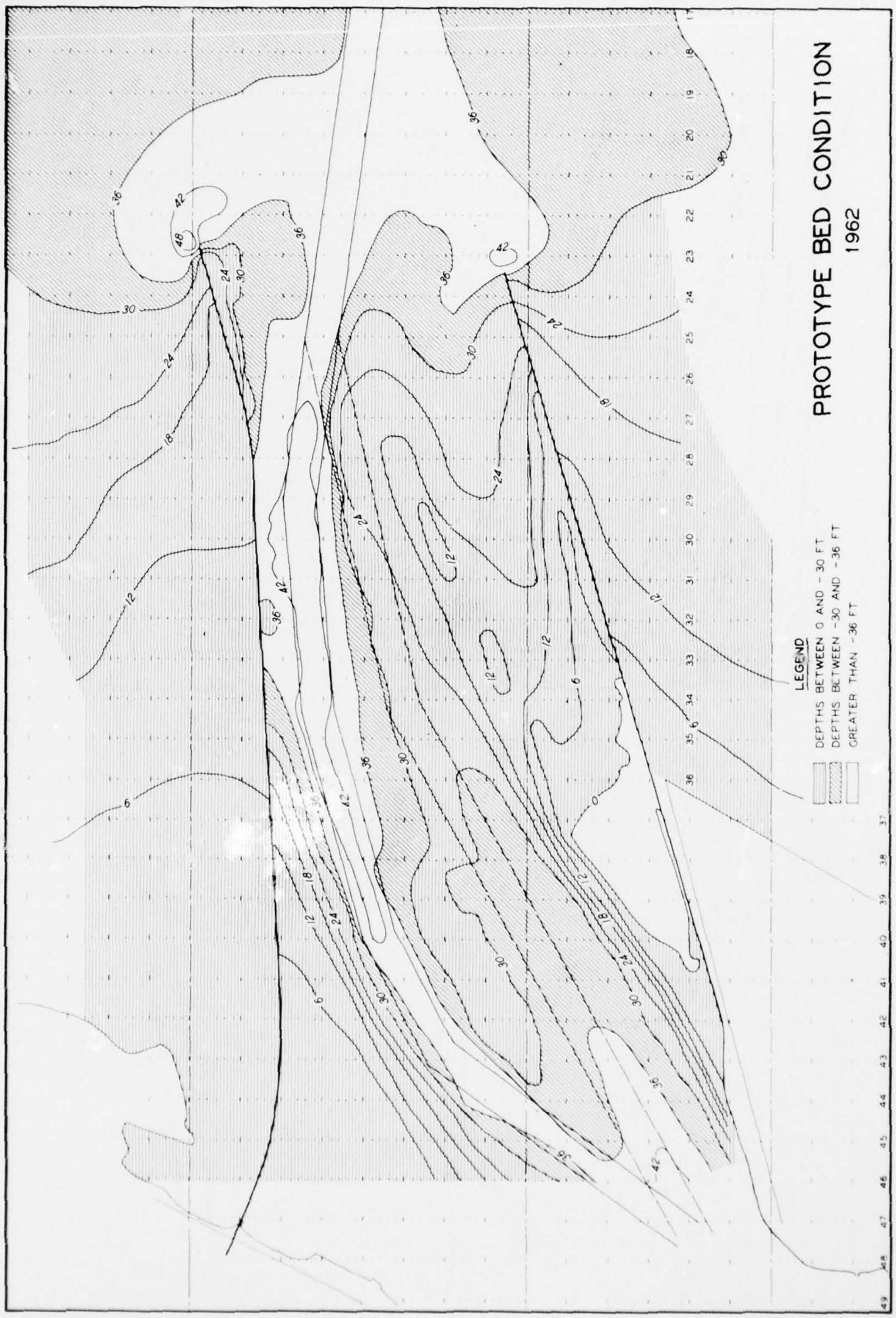
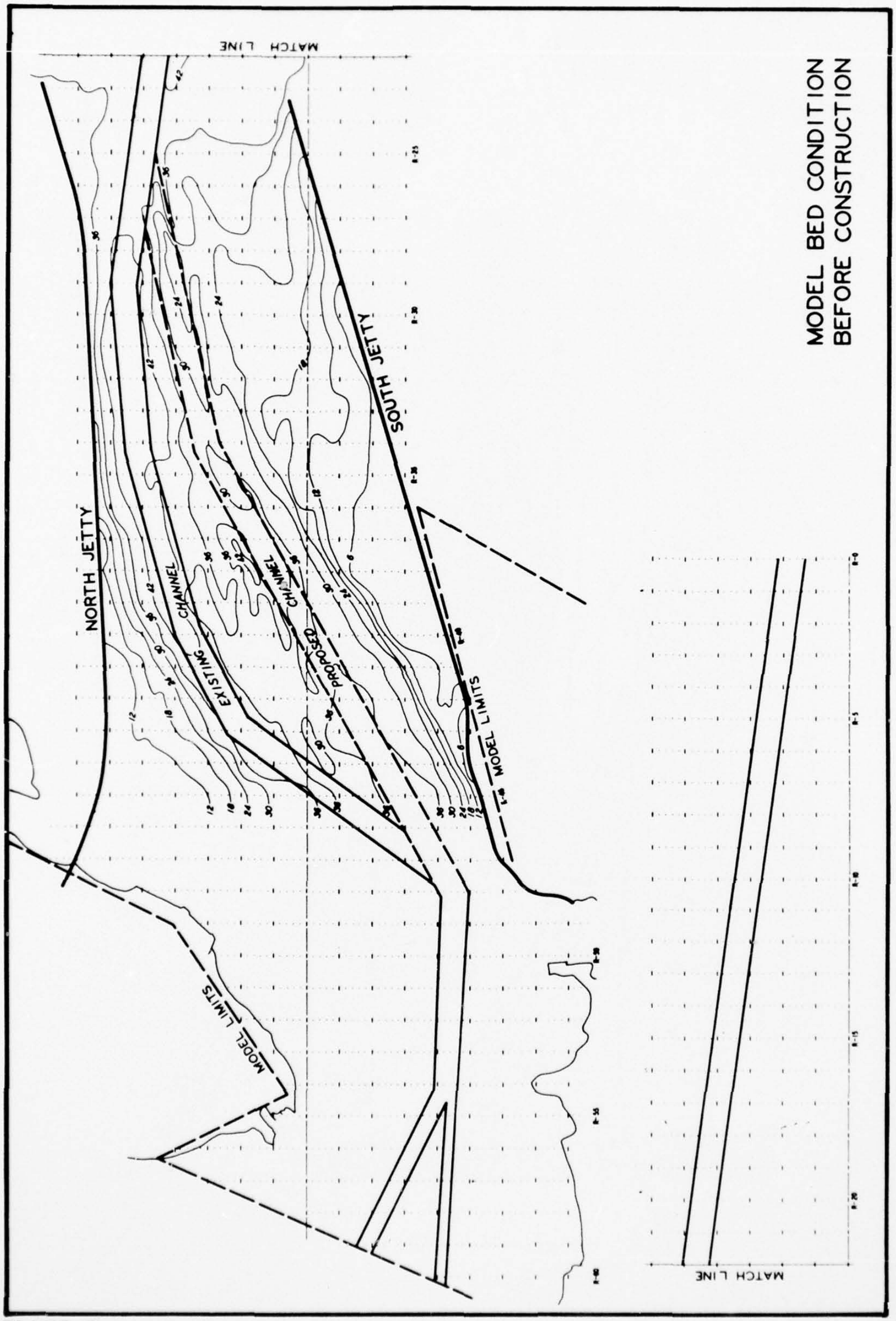
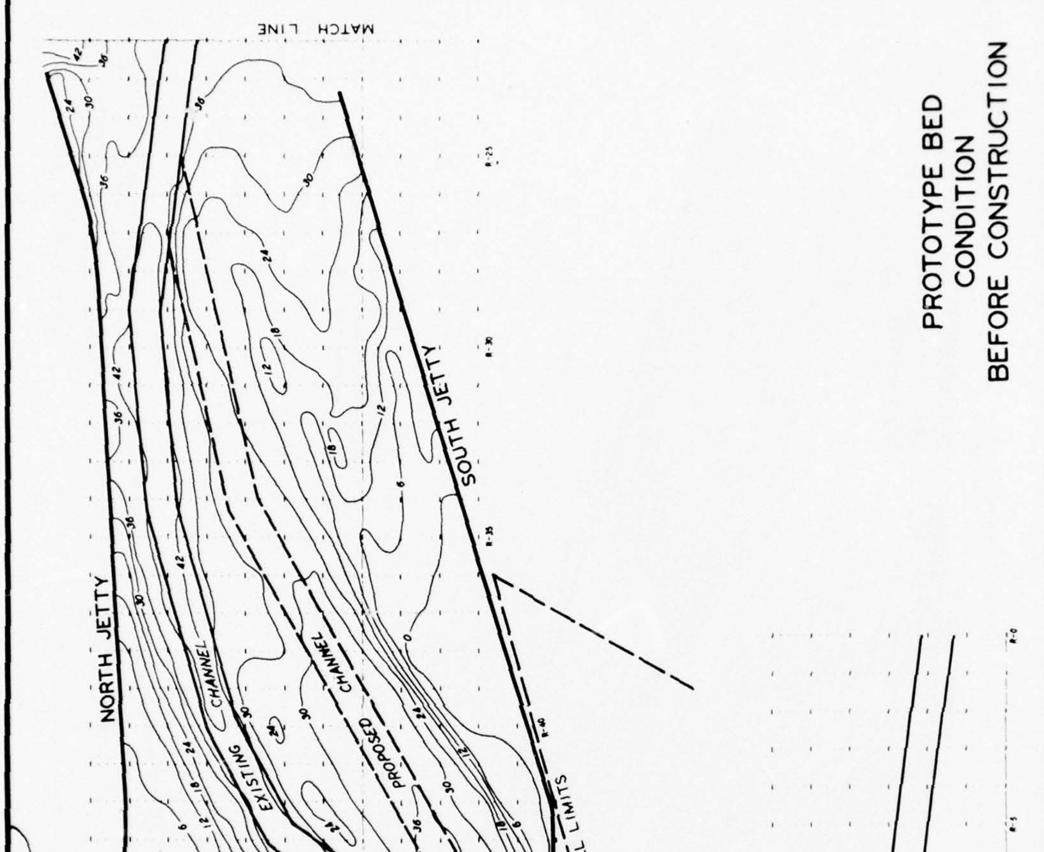

PROTOTYPE BED CONDITION
1962
LEGEND
DEPTHS BETWEEN 0 AND -30 FT
DEPTHS BETWEEN -30 AND -36 FT
GREATER THAN -36 FT

PLATE 61

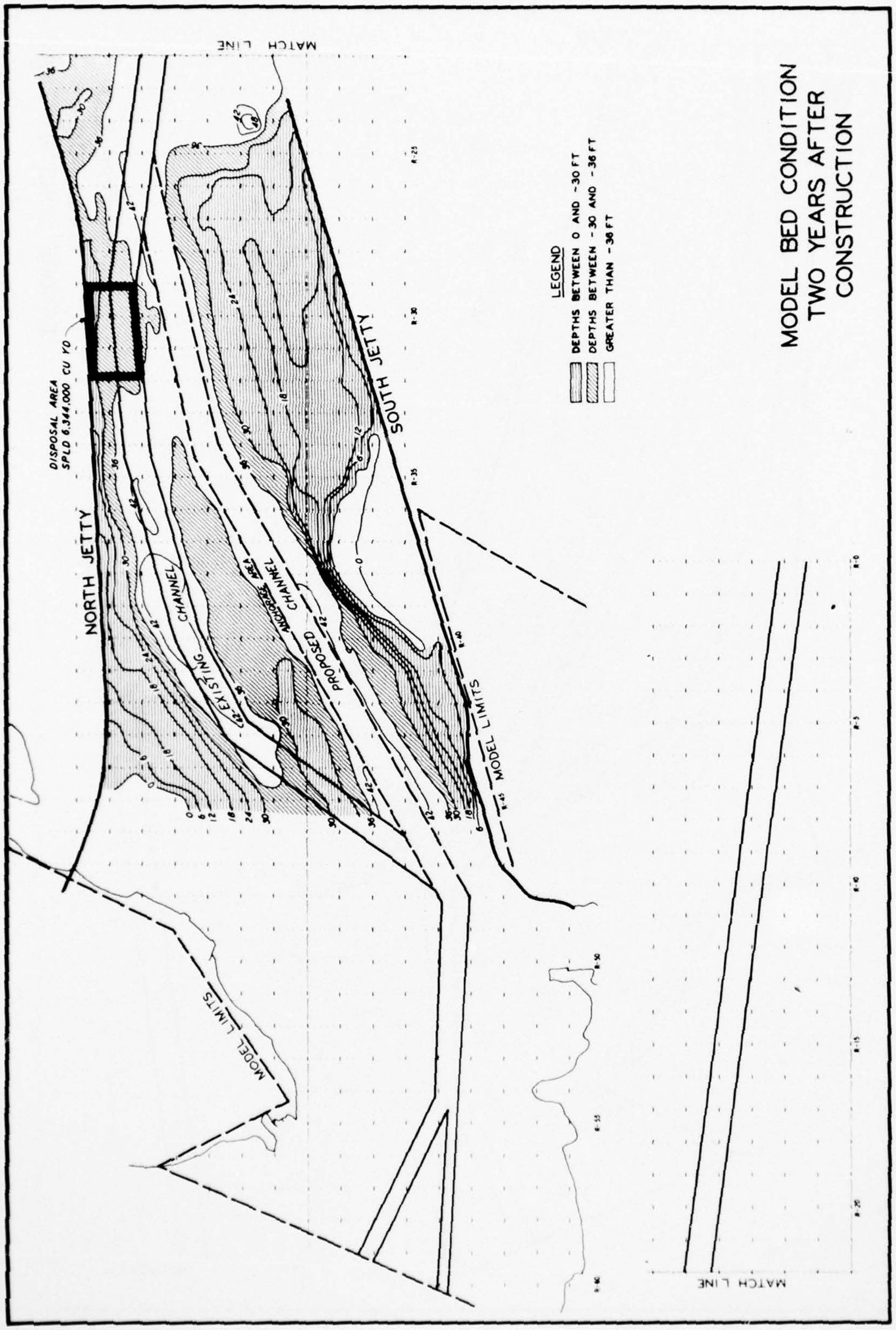


MODEL BED CONDITION
BEFORE CONSTRUCTION

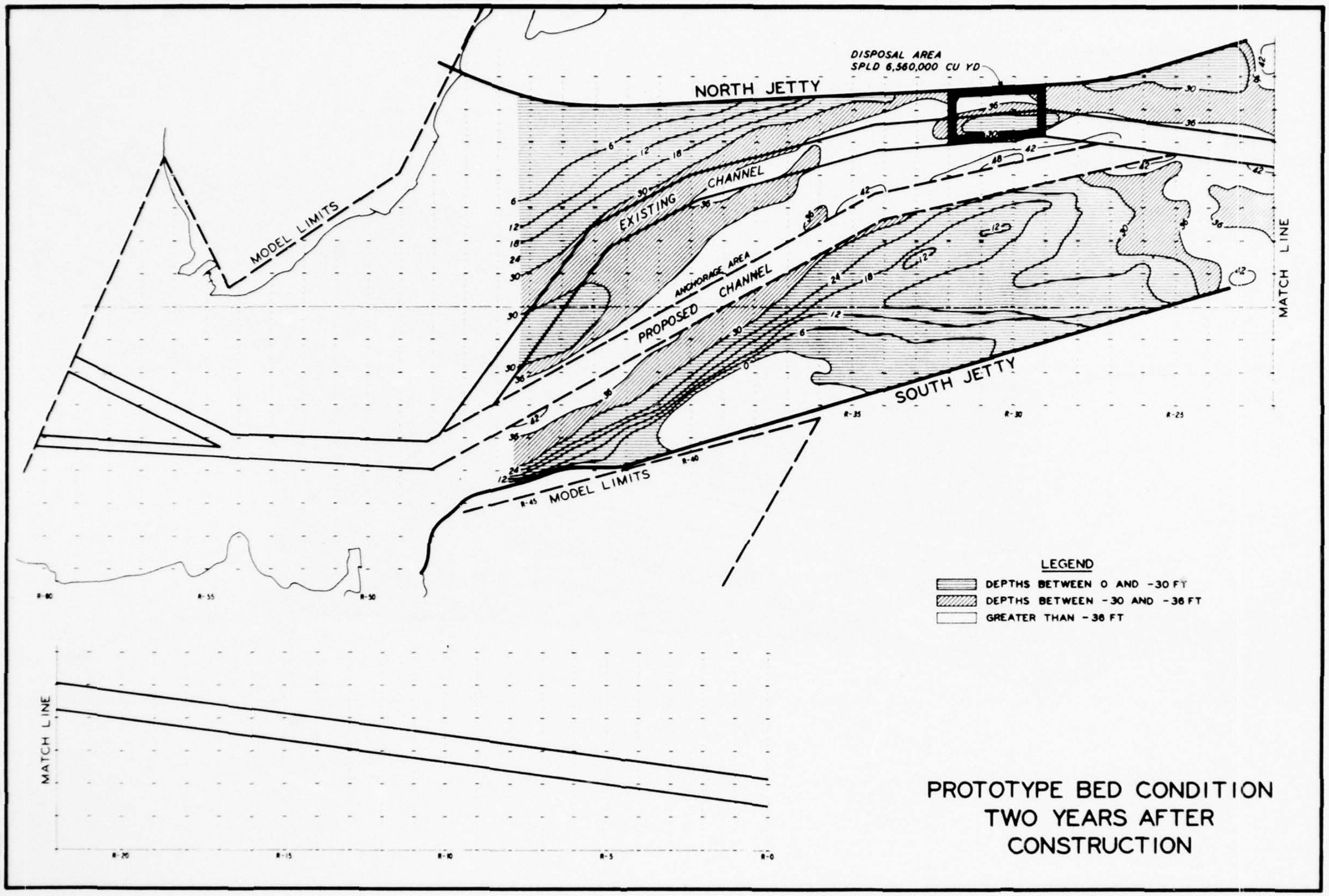
PLATE 62



PROTOTYPE BED
CONDITION
BEFORE CONSTRUCTION



MODEL BED CONDITION
TWO YEARS AFTER
CONSTRUCTION



PROTOTYPE BED CONDITION
TWO YEARS AFTER
CONSTRUCTION

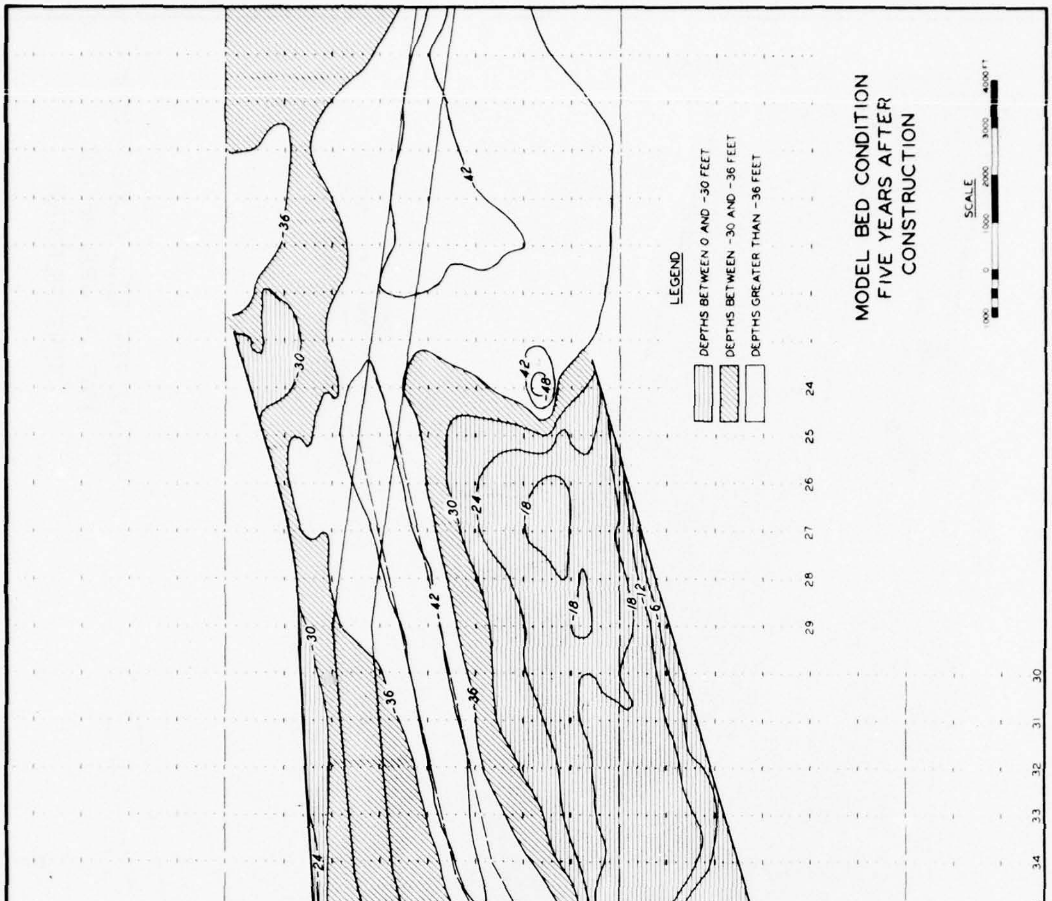
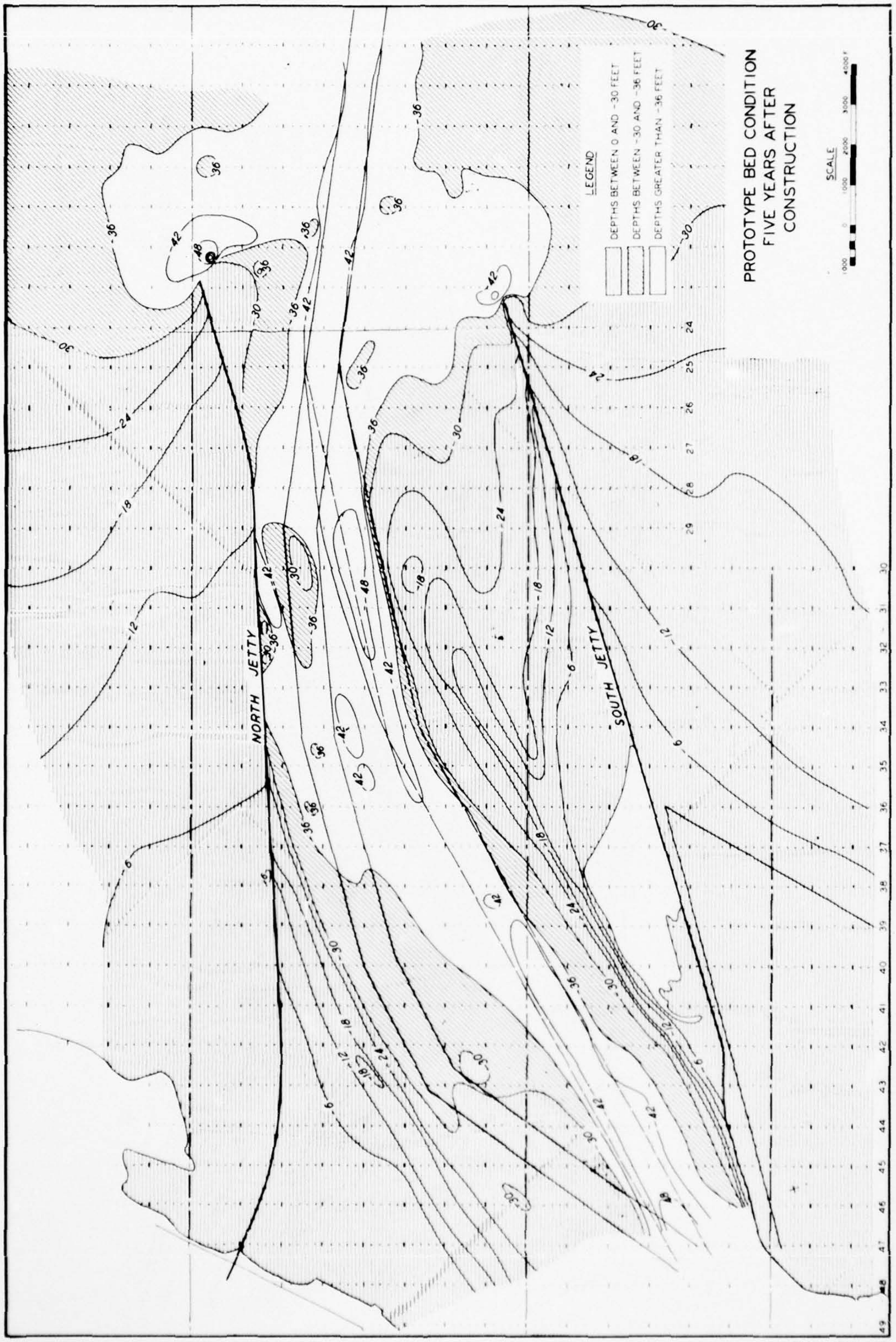

MODEL BED CONDITION
FIVE YEARS AFTER
CONSTRUCTION
LEGEND
DEPTHS BETWEEN 0 AND -30 FEET
DEPTHS BETWEEN -30 AND -36 FEET
DEPTHS GREATER THAN -36 FEET
SCALE

PLATE 66


PROTOTYPE BED CONDITION
FIVE YEARS AFTER
CONSTRUCTION
LEGEND
DEPTHS BETWEEN 0 AND -30 FEET
DEPTHS BETWEEN -30 AND -36 FEET
DEPTHS GREATER THAN -36 FEET
SCALE
NORTH JETTY
SOUTH JETTY

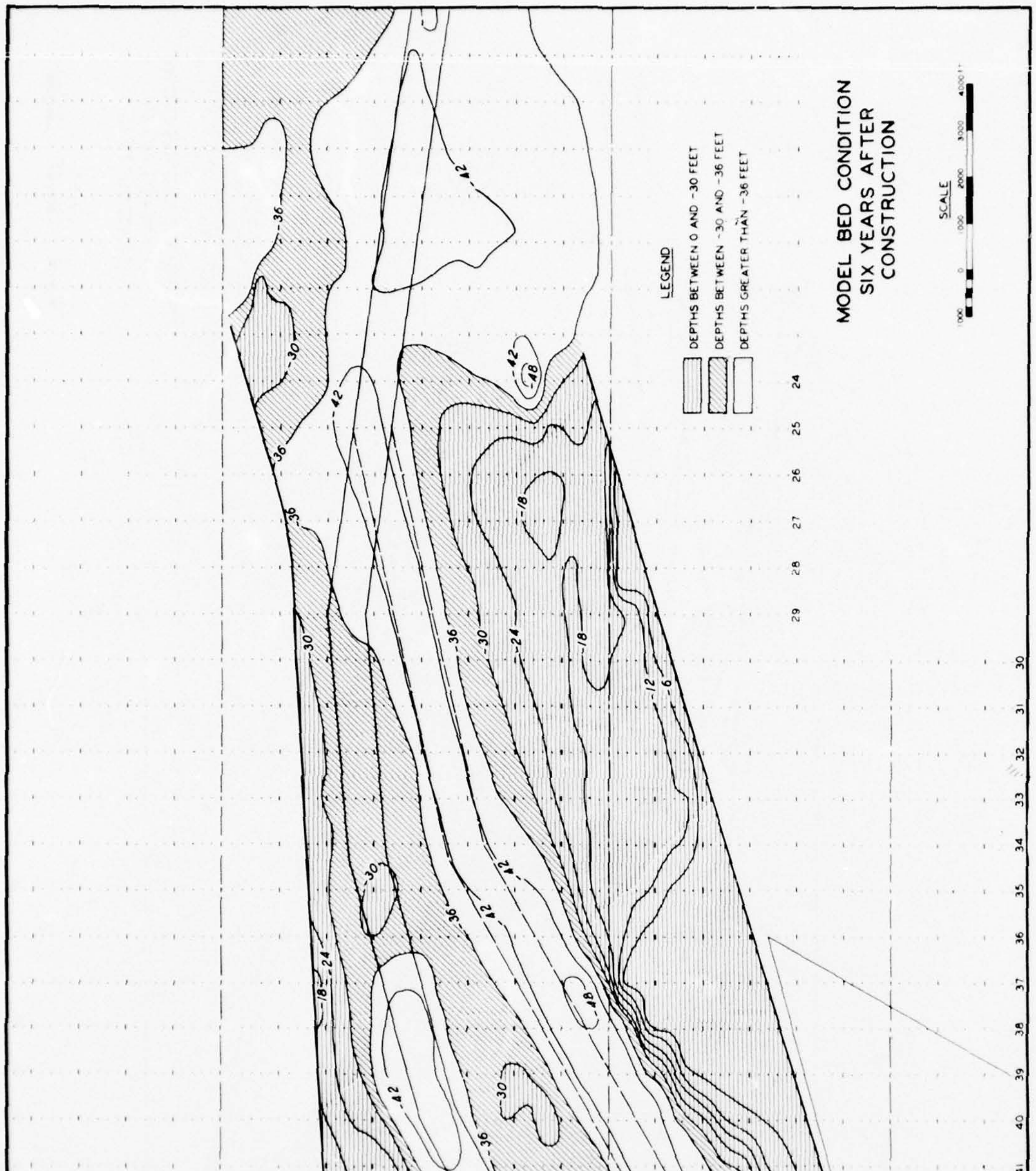

MODEL BED CONDITION
SIX YEARS AFTER
CONSTRUCTION
LEGEND
DEPTHS BETWEEN 0 AND -30 FEET
DEPTHS BETWEEN -30 AND -36 FEET
DEPTHS GREATER THAN -36 FEET
SCALE

PLATE 68

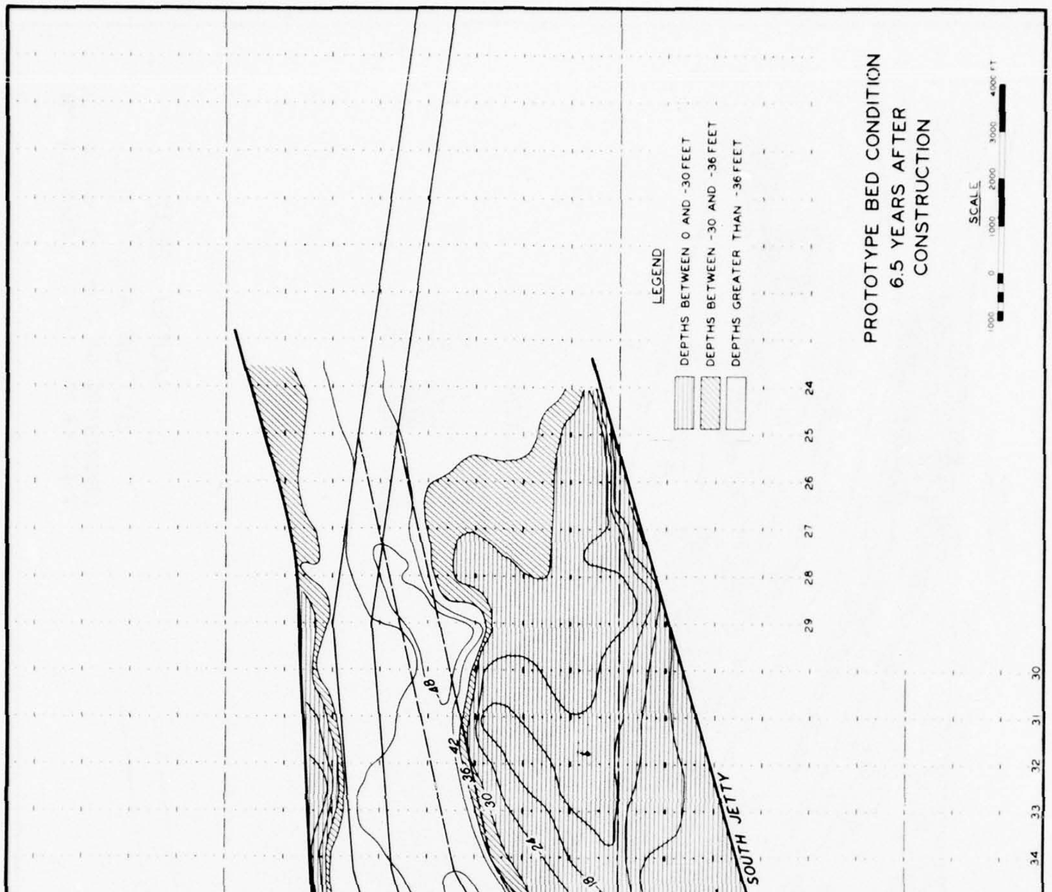

PROTOTYPE BED CONDITION
6.5 YEARS AFTER
CONSTRUCTION
LEGEND
DEPTHS BETWEEN 0 AND -30 FEET
DEPTHS BETWEEN -30 AND -36 FEET
DEPTHS GREATER THAN -36 FEET
SCALE
1000 0 1000 2000 3000 4000 FT
NORTH JETTY
SOUTH JETTY

PLATE 69

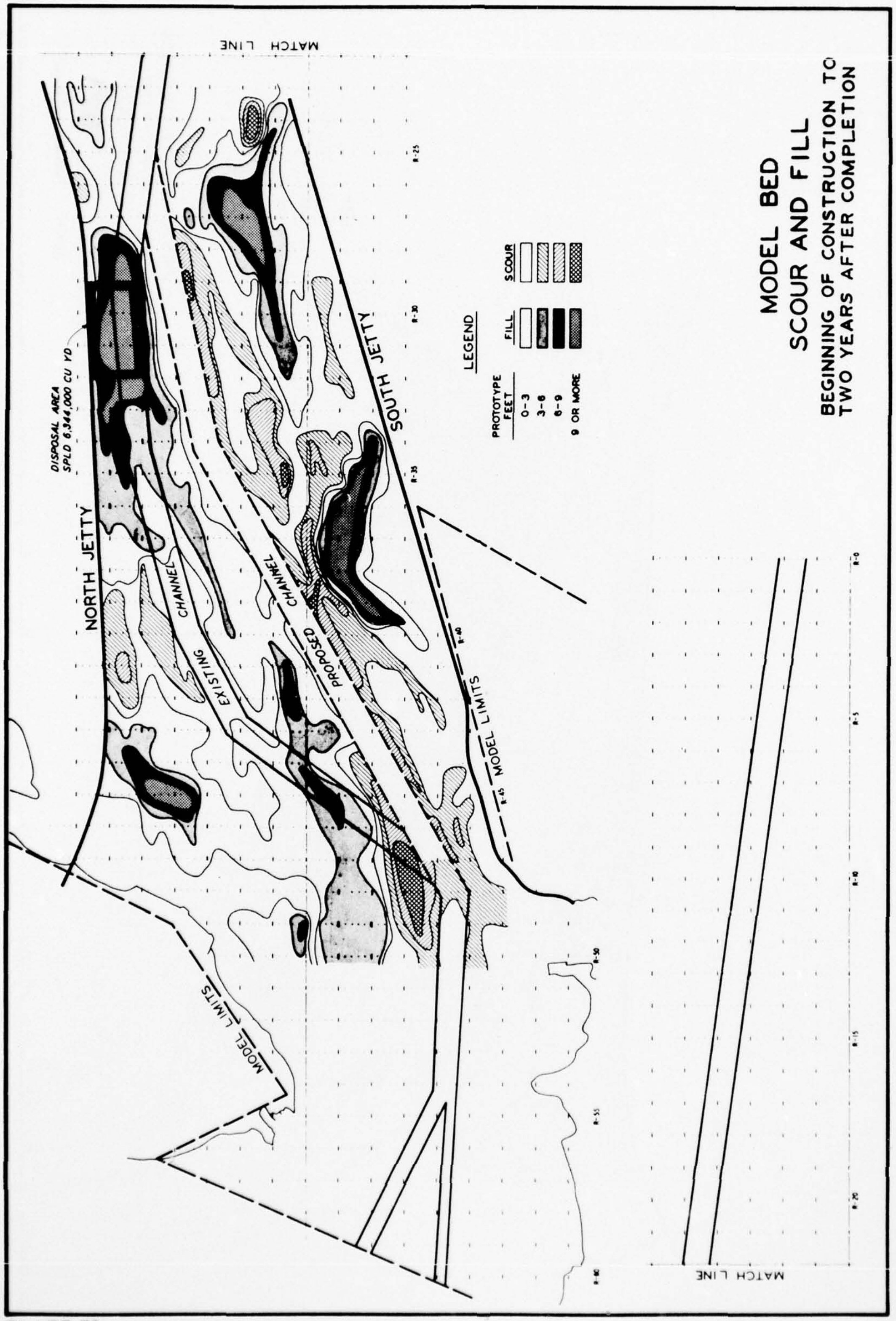
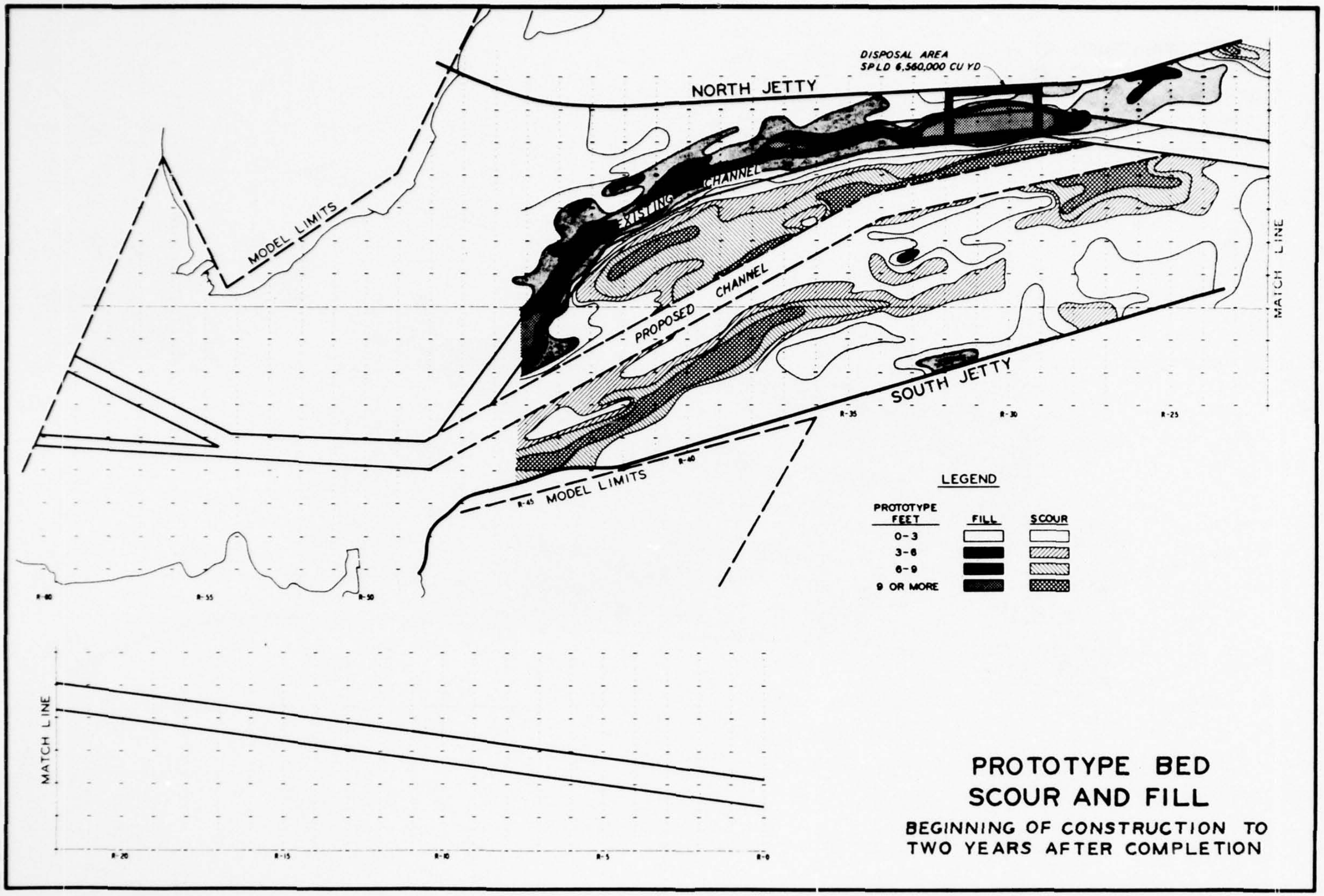

MODEL BED
SCOUR AND FILL
BEGINNING OF CONSTRUCTION TO
TWO YEARS AFTER COMPLETION
LEGEND
PROTOTYPE FEET
0-3
3-6
6-9
9 OR MORE
FILL
SCOUR
NORTH JETTY
SOUTH JETTY
EXISTING CHANNEL
PROPOSED CHANNEL
DISPOSAL AREA
SPLD 6,344,000 CU YD
MODEL LIMITS
MODEL LIMITS
MATCH LINE
MATCH LINE

PLATE 70



PROTOTYPE BED
SCOUR AND FILL
BEGINNING OF CONSTRUCTION TO
TWO YEARS AFTER COMPLETION

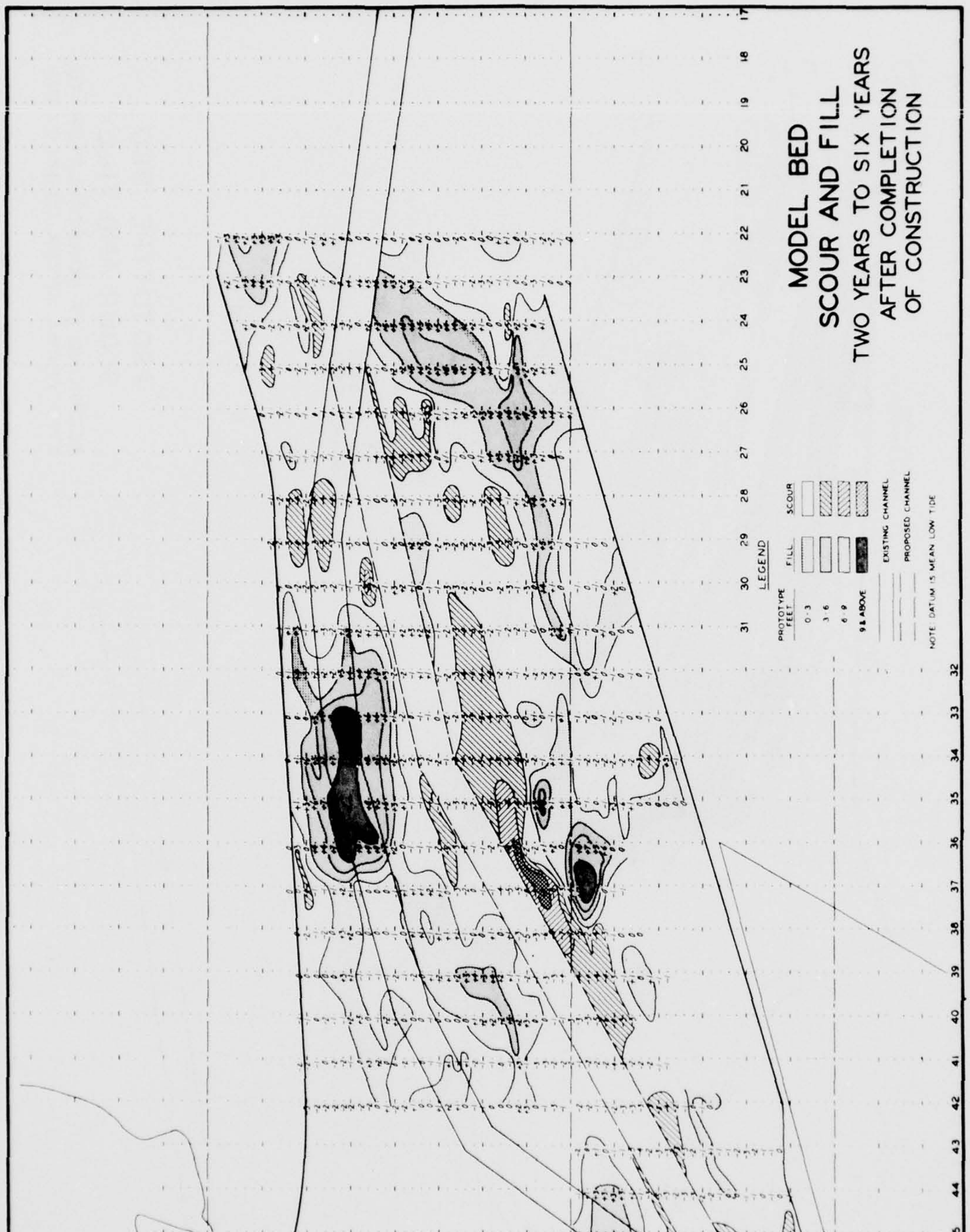

MODEL BED
SCOUR AND FILL
TWO YEARS TO SIX YEARS
AFTER COMPLETION
OF CONSTRUCTION
LEGEND
PROTOTYPE FEET
FILL
SCOUR
0-3
3-6
6-9
9 & ABOVE
EXISTING CHANNEL
PROPOSED CHANNEL
NOTE: DATUM IS MEAN LOW TIDE
17
18
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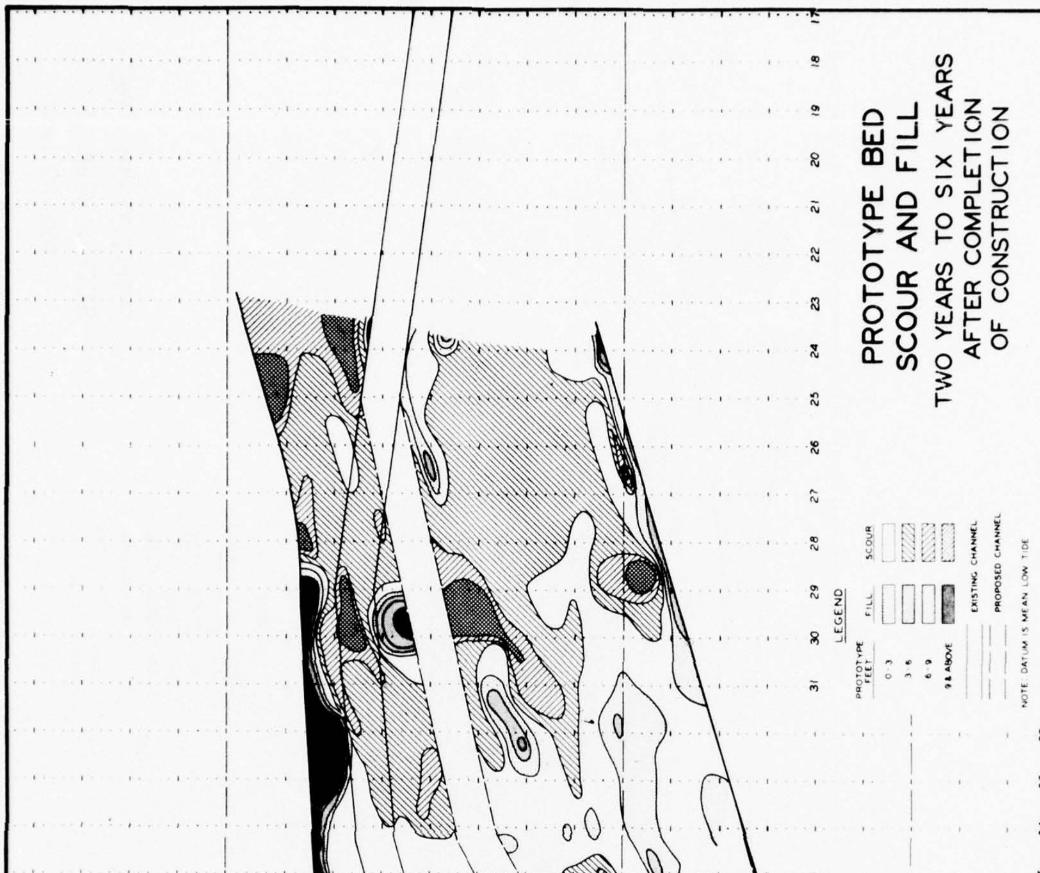
PLATE 72


PROTOTYPE BED
SCOUR AND FILL
TWO YEARS TO SIX YEARS
AFTER COMPLETION
OF CONSTRUCTION
LEGEND
PROTOTYPE FEET
FILL
SCOUR
0-3
3-6
6-9
9 & ABOVE
EXISTING CHANNEL
PROPOSED CHANNEL
NOTE: DATUM IS MEAN LOW TIDE

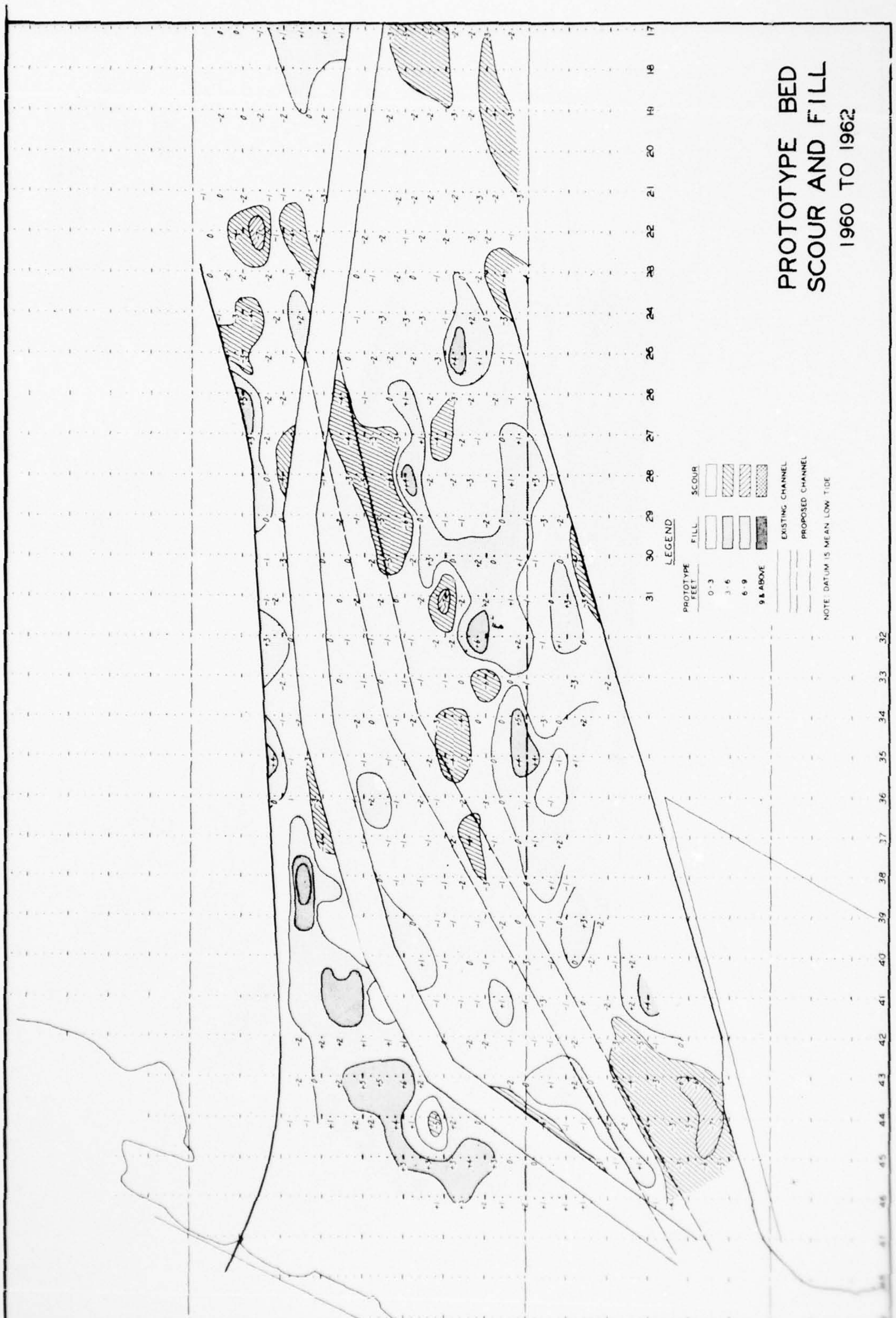

PROTOTYPE BED
SCOUR AND FILL
1960 TO 1962
LEGEND
PROTOTYPE FEET
FILL
SCOUR
0-3
3-6
6-9
9 & ABOVE
EXISTING CHANNEL
PROPOSED CHANNEL
NOTE DATUM IS MEAN LOW TIDE

PLATE 74

AD-A047 988 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MISS F/G 8/8
PHYSICAL HYDRAULIC MODELS: ASSESSMENT OF PREDICTIVE CAPABILITIE--ETC(U)
NOV 77 J V LETTER, W H MCANALLY

UNCLASSIFIED AEWES-RR-H-75-3-2 NL

3 OF 3
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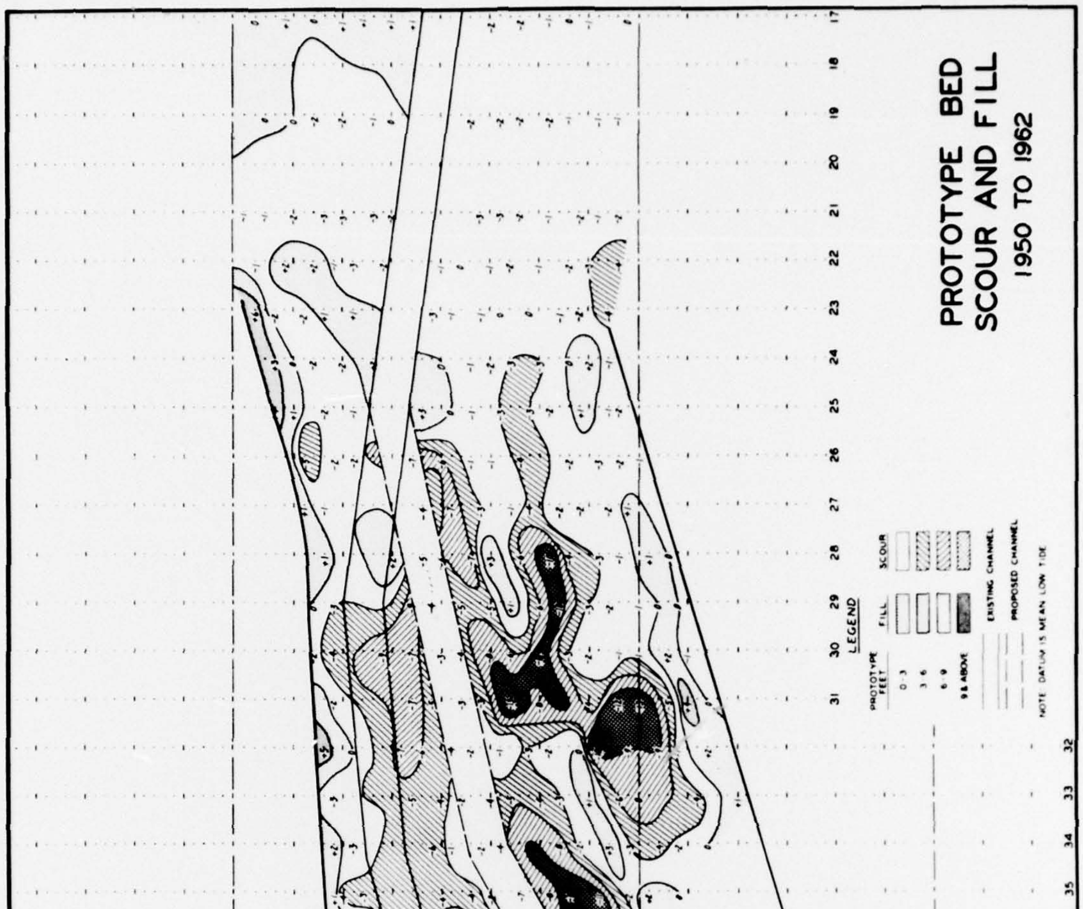
PROTOTYPE BED
SCOUR AND FILL
1950 TO 1962
LEGEND
PROTOTYPE FEET
FILL
SCOUR
0-3
3-6
6-9
9 & ABOVE
EXISTING CHANNEL
PROPOSED CHANNEL
NOTE: DATUM IS MEAN LOW TIDE

PLATE 75

APPENDIX A: NOTATION

A_c	Vertical cross-sectional area
A_s	Horizontal surface area
AD_u	Reported dredged volume adjusted for underdepth
AD_{uo}	Reported dredged volume adjusted for underdepth and overdepth
d	Representative sediment grain size
f	Darcy-Weisbach friction factor
F_*	Particle densimetric Froude number
g	Acceleration due to gravity
g_s	Sediment transport rate in weight per time per unit width
h	Water depth
h/λ	Relative water depth
H	Wave or tide height
H/λ	Wave steepness
k_s	Equivalent bed roughness size
OD	Overdepth volume for year under consideration
OD'	Overdepth volume for year prior to year under consideration
Q	Volume flow rate
r	As a subscript, a model to prototype ratio of the subscripted variable
R	Hydraulic radius
RD	Reported dredged volume
Re	Reynold's number
R_*	Particle Reynolds number
S_e	Energy grade-line slope
t	Time
T	Wave or tidal period
u	Current speed
u_*	Shear velocity
UD	Underdepth volume for the year under consideration
UD'	Underdepth volume for the year prior to year under consideration
UT/λ	Current parameter
V	Volume

X	Characteristic horizontal length
Y	Characteristic vertical length
α	Wave refraction angle
γ	Unit weight of water
γ_s	Unit weight of sediment particles
γ'	Submerged unit weight of sediment particles
Δ_{F_*}	Scale factor for particle Froude number
Δ_{R_*}	Scale factor for particle Reynolds number
λ	Wavelength
ν	Kinematic viscosity of water
ρ	Density of water
τ_o	Average bottom shear stress
Φ	Sediment transport function

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Letter, Joseph V

Physical hydraulic models: assessment of predictive capabilities; Report 2: Movable-bed model of Galveston Harbor entrance / by Joseph V. Letter, Jr., William H. McAnally, Jr. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.

92, [25] p., 75 leaves of plates : ill. ; 27 cm. (Research report - U. S. Army Engineer Waterways Experiment Station ; H-75-3, Report 2)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.

References: p.91-92.

1. Galveston Harbor. 2. Hydraulic models. 3. Movable-bed models. 4. Navigation channels. 5. Prediction. I. McAnally, William H., joint author. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Research report ; H-75-3, Report 2.

TA7.W34r no.H-75-3 Report 2